WMA

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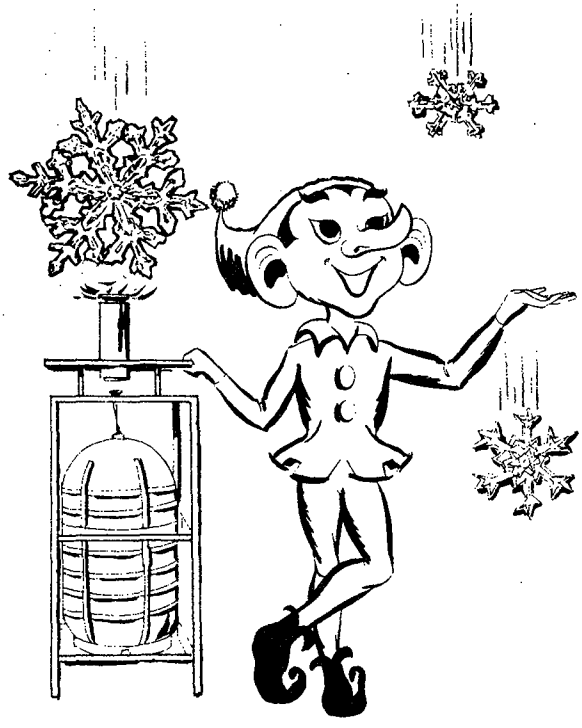
Cover Photograph

This photograph shows a "typical" hail producing cumulus development in northeast Colorado. View is looking easterly froma point near New Raymer. The cell is moving away from the camera site and both hail and rain are falling from the trailing edge of the system. Inflow important to the precipitation mechanism is clearly visible immediately left of the rain and hail shaft.

Photograph by Thomas J. Henderson,
Atmospherics Incorporated,
Fresno, California



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SHORT NOTE

AN OPERATIONAL CLOUD-SEEDING PROJECT IN RHODESIA

by

J.E. Stevens[1] and J.M. Gosnell[2]

INTRODUCTION

Three years of experimental cloud seeding by the Rhodesia Meteorological Department determined certain local criteria for successful cloud seeding using the acetone burner method. In particular it demonstrated that under suitable conditions natural falls of about 0.15" could be augmented to 0.4" - 0.5" (Rhodesia Met. Department Notes A 29[3] and 35[4]). This was the basis of the decision to undertake an operational seeding project during 1971-72.

DESCRIPTION OF AREA

As shown on the accompanying map, the target area comprises the catchment of two dams, Kyle and Bangala, in the central portion of Rhodesia. These dams provide irrigation water for agricultural development, mainly sugarcane, in the Sabi Limpopo Authority area. The catchments total 2 300 sq. miles, and make a target of some 90 x 30 miles approximately centred on Fort Victoria (lat. 20°S, long. 31°E). In the north the elevation is over 4 000 ft. The terrain gradually falls for nearly 60 miles to the Kyle Dam, just below 3 400 ft and area approximately 35 sq. miles. From the hills around the Dam the ground falls away fairly rapidly to the south with the Bangala Dam at the southern extremity in flat country just below 2 000 ft.

METEOROLOGICAL CHARACTERISTICS

The rainy season in Rhodesia is from November to March inclusive, but the dates of beginning and end of the season vary from year to year. The Inter-Tropical Convergence Zone (I.T.C.Z.) usually brings rain to the northern half of Rhodesia, but seldom penetrates as far south as the catchment area. To the south lies the Sub-Tropical Anticyclone with its low rainfall characteristics. The catchment area generally has a lower rainfall than the main crop growing areas in the northern part of the country. The average rainfall is about 28", locally higher over the hilly country around the Kyle Dam but lower over the low-lying country in the south.

Because of the intermediate position of the catchment between wetter and drier regimes, the rainfall varies considerably from year to year, the normal variation being 40% of the mean value. Heavier rainfall occurs when the I.T.C.Z. is further south than usual and pressure fluctuations of the Sub-Tropical Anticyclone cause convergence. Run-off into the Kyle Dam depends mainly upon this synoptic situation. In the occasional good season this situation is repeated frequently.

Far more often, the influence of the high pressure system to the south predominates and the rainfall comes from light convective showers. More than half the years generally have less than 24"; as little as 14" has been experienced. Although the catchment is in a lower rainfall area it has twice as many heavy falls of 2" or more as in most of the country. This means that half the catchment's rain is spread among 90% of the season's 55 or so rain days.

OBJECT OF THE OPERATION

These meteorological characteristics make the area a suitable subject for cloud seeding. Seeding certainly stands to help farming and by helping to sustain rainfall during lean periods, allows the run-off from the periodic spell of heavy rain to flow without undue delay. This is probably the manner in which seeding makes its main contribution to run-off.

The ultimate aim of the operation is to increase run-off into the two major dams, Kyle and Bangala, in order to supplement irrigation water requirements for the Lowveld sugarcane development.

THE SEEDING OPERATION

The Meteorological Department prepares a daily forecast of seedability, using its reporting network, in particular the radiosonde data from Bulawayo and Salisbury; upper wind data to allow for drift of seeded clouds and on the spot advice from the Meteorological Officer at Fort Victoria.

A_6computer programme based on the work of D.A. Andrews[5] and the Simpson[6] Florida 'P' Model is being developed and it is hoped to use this in the future.

A turbo charged Cessna 210 has been equipped with fitted Very pistols and a chute for the discharge of dry ice in the side of the aircraft. The principal method is to use manually fired pyrotechnics containing silver iodate, while dry ice is also being used as an alternative method.

Following on from the findings of Slusher[7] and Scheffee[7] the cartridges now being used more closely correspond with the formulation favoured by St. Amand[8,9]. Two types of cartridge are used, each having 90 gm of seeding mixture,

	TB-1	TB-2
Silver iodate	78.3%	24.1%
Potassium nitrate	0%	43.7%
Aluminium	10.8%	18.0%
Magnesium	5.2%	8.1%
Binder	5.7%	6.0%

plus ejection charge and first fire mixture.

The seeding technique is to select a cloud with top at $-10^{o}C$ (22,000 ft.) or colder, and to fire one or two cartridges into a growing turrett. Sometimes higher tops are seeded. If there is nothing to lose, tops as warm as $-5^{o}C$ may be seeded. In all cases, the meteorologist keeps a careful record of the time and location of seedings and any observed results. The TB-2 cartridge is the type most frequently used.

In the alternative method, dry ice is broken up manually and kept in polystyrene containers in the aircraft. Up to 20 lb is placed at a time in the chute and can be released instantly or gradually.

EVALUATION

Final assessment of the success of the operation will be based on -

a) Visual observations by the meteorologist carrying out the seeding operation.

b) Visual observation submitted by ground observers.

c) Comparison of the daily rainguage records with the seeding log for the same day.

d) Comparison of the rainfall of the catchment area with that in neighbouring areas using a ranking method over a number of year's records.

a), b) and c) will be necessary to supplement d) due to the comparatively high variability of rainfall in the area both in time and from place to place.

In the meantime visual observations give grounds for optimism that the operation will be successful.

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2. Officer-in-Charge, Rhodesia Sugar Association Experiment Station.

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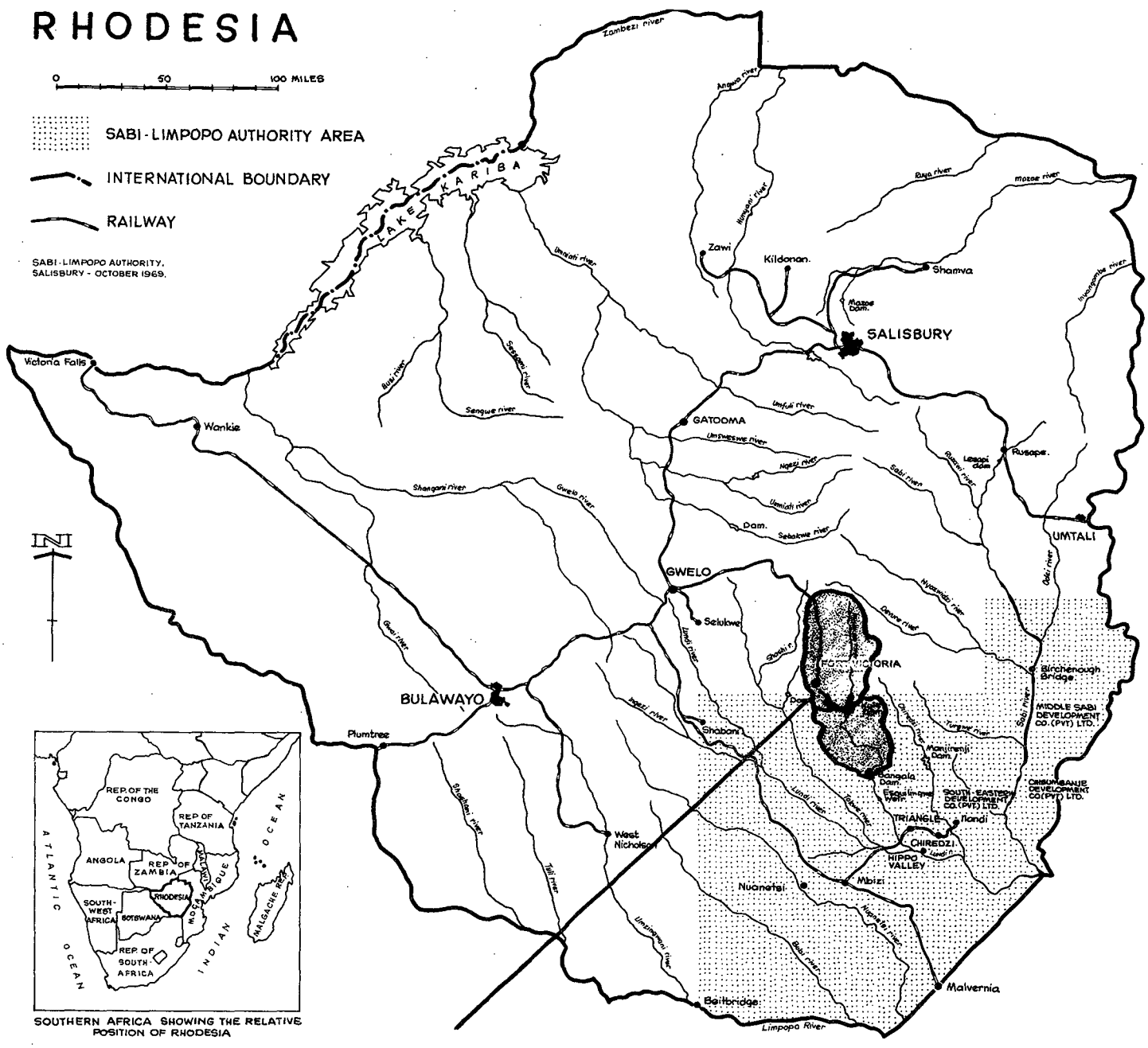


SOUTHERN AFRICA SHOWING THE RELATIVE POSITION OF RHODESIA

KYLE AND BANGALA CATCHMENTS

WEATHER MODIFICATION IN TEXAS*

by

John T. Carr, Jr.**

ABSTRACT

A total of four officially sanctioned or licensed and permitted weather modification operations were conducted in Texas during calendar year 1971. All four operations utilized aircraft for seeding purposes. Two of the officially sanctioned operations, one an experiment and the other a drought relief operation, were managed by the Bureau of Reclamation. Two operations, one for both hail suppression and precipitation stimulation and one for precipitation stimulation alone, were privately financed and conducted by a licensed and permitted weather modification firm. Two unlicensed operators are reported to have been performing unpermitted "rainmaking" operations with ground based equipment during the year.

COLORADO RIVER MUNICIPAL WATER DISTRICT

Atmospherics Incorporated of Fresno, California, is conducting a weather modification activity for this district. The district is paying for this operation which covers an area of about 3500 square miles in all or parts of fourteen counties. The goal of this operation is to increase precipitation in a drainage area above a reservoir during the period April 15 to October 15, 1971. The texas Water Development Board has awarded a contract for evaluation of this project. Preliminary results are expected to be available early in 1972.

PLAINS WEATHER IMPROVEMENT ASSOCIATION

Atmospherics Incorporated of Fresno, California, is conducting a hail suppression program for this association. The association is funding this program with funds raised from the local people interested in the program. The area covered by this program is limited to all or parts of 12 counties, with the main target being Lamb, Floyd and Hale Counties.

*Prepared for presentation to the Arkansas-White-Red Basins Inter-Agency Committee, Kansas City, Missouri, October 20, 1971.

**Certified Consulting Meteorologist and Assistant to Executive Director, Texas Water Development Board, Austin, Texas.

The two-fold goal of this program is hail suppression and precipitation enhancement. Clouds will be seeded during the period May through October, so no 1971 results are available. However, the report on the 1970 operation in the same area reveals the following:

TEXAS HAIL SUPPRESSION PROJECT

OPERATIONAL SUMMARY, 14 May 1970 - 15 September 1970:

COMBINED TOTALS (for 3 aircraft);

OPERATIONAL DAYS - 28

FLIGHTS:

Total number - 83
Total hours - 133.7
Average flight time per flight - 1.61 hrs.
Average flight time per operational day - 4.95 hrs.

FLARES:

Total number of "102" (30 gm) type used - 578
Total number of "105" (70 gm) type used - 198
Percentage of all flares used where the high-powered (70 gm) flare was required - 25.5%
Average number of flares used per cell - 3.8
Average number of flares used per operational day - 27.6
Total Silver Iodide - 31.37 Kg, about 69 lbs.

THUNDERSTORM CELLS SEEDED - 204

TOTAL RADAR SURVEILLANCE - 214 hrs.

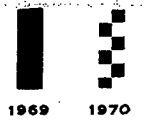
Figures 1 through 4 depict reported hail losses and rainfall comparisons for the years 1969 and 70 in the target area and surrounding counties, as well as statistics on the flights made by Atmospherics, Incorporated, while under a hail suppression contract awarded by Plains Weather Improvement Association in 1970.

TEXAS HIGH PLAINS

ESTIMATED ACRES OF COTTON LOST OR DAMAGED BY HAIL

% COMPARISON OF YEARS 1969 - 1970

Compiled by County Agents



TARGET AREA: Hale, Lamb and small part of Floyd.

NOT IN PROGRAM: Briscoe and Hockley.

BUFFER ZONE: Swisher, Floyd, Bailey and Lubbock (approximately ½ of each county nearest target area).

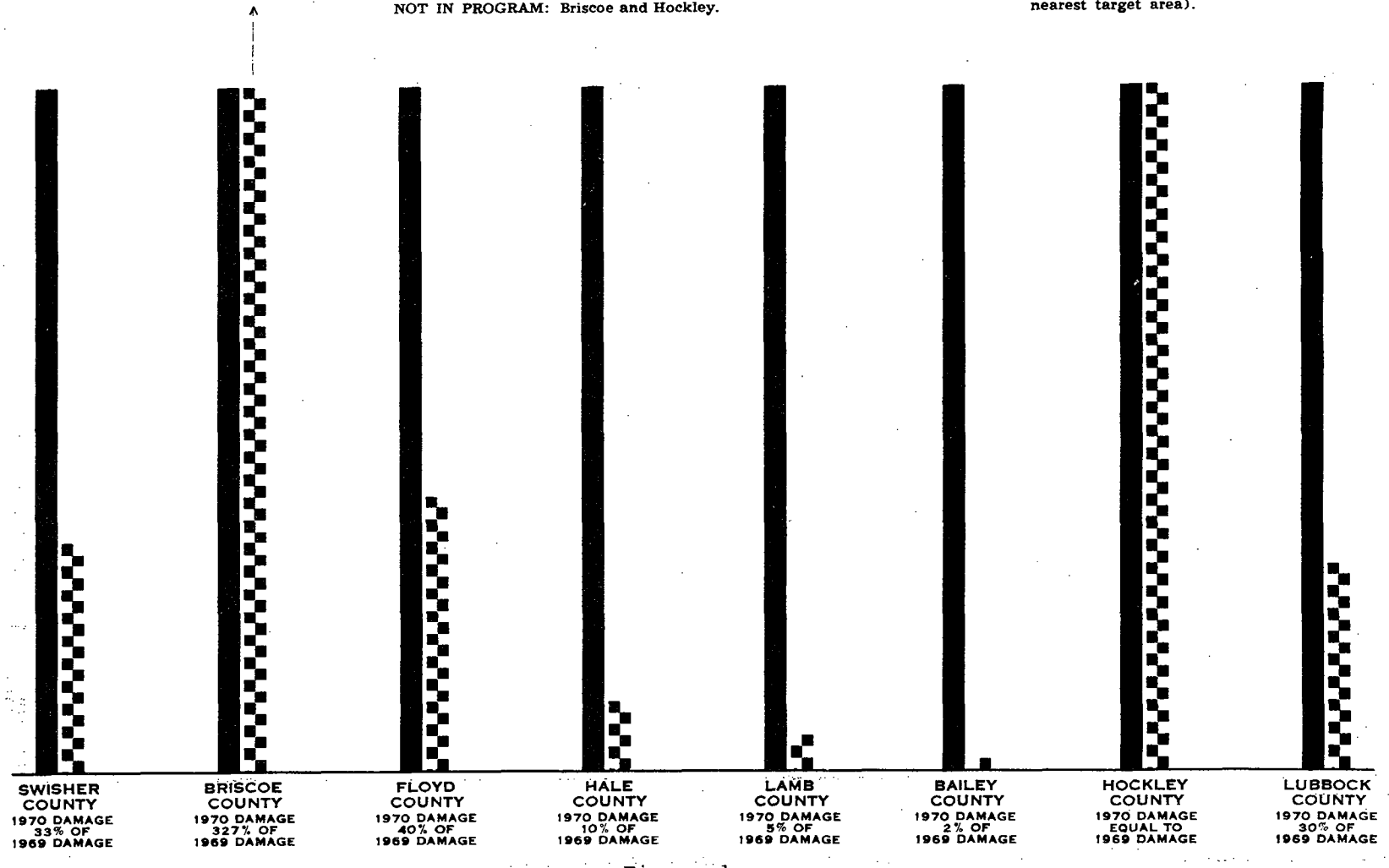

SWISHER COUNTY
1970 DAMAGE 33% OF 1969 DAMAGE
BRISCOE COUNTY
1970 DAMAGE 327% OF 1969 DAMAGE
FLOYD COUNTY
1970 DAMAGE 40% OF 1969 DAMAGE
HALE COUNTY
1970 DAMAGE 10% OF 1969 DAMAGE
LAMB COUNTY
1970 DAMAGE 5% OF 1969 DAMAGE
BAILEY COUNTY
1970 DAMAGE 2% OF 1969 DAMAGE
HOCKLEY COUNTY
1970 DAMAGE EQUAL TO 1969 DAMAGE
LUBBOCK COUNTY
1970 DAMAGE 30% OF 1969 DAMAGE

Figure 1

PLAINS WEATHER IMPROVEMENT ASSOCIATION

Flights, Time and Material, 1970

Date	Number of Flights	Hours Flown	Number of Flares Used
May 14	4	8.7 hours	41
May 23	4	9.2 hours	35
May 25	5	9.9 hours	62
May 26	5	8.0 hours	34
May 28	1	.5 hours	1
May 29	5	9.1 hours	59
May 30	1	1.2 hours	6
May 31	3	6.0 hours	53
TOTALS	28	52.6 hours	291
June 7	4	8.0 hours	60
June 8	6	7.5 hours	43
June 9	2	1.3 hours	4
June 13	4	7.4 hours	61
June 15	2	2.9 hours	4
June 17	1	1.5 hours	16
June 18	3	2.9 hours	6
June 20	4	7.0 hours	42
June 25	3	4.9 hours	27
June 29	1	1.8 hours	3
TOTALS	30	45.4 hours	266
July 11	1	.9 hours	2
July 15	1	1.9 hours	11
July 24	1	.7 hours	1
July 29	1	.6 hours	2
July 30	1	1.2 hours	4
TOTALS	5	5.3 hours	20
August 13	1	.6 hours	2
August 20	5	6.0 hours	38
August 21	3	4.7 hours	46
TOTALS	9	11.3 hours	86
Sept. 2	3	5.2 hours	39
Sept. 8	3	4.6 hours	21
Sept. 9	4	6.2 hours	45
TOTALS	10	16.0 hours	105
GRAND TOTAL	82	131.8 hours	776

29 operational days; Used 31,370 grams of Silver Iodide.

60% of operational time was at night.

Figure 2

ANNUAL RAINFALL — 1969 - 1970

Compiled by U. S. Weather Service

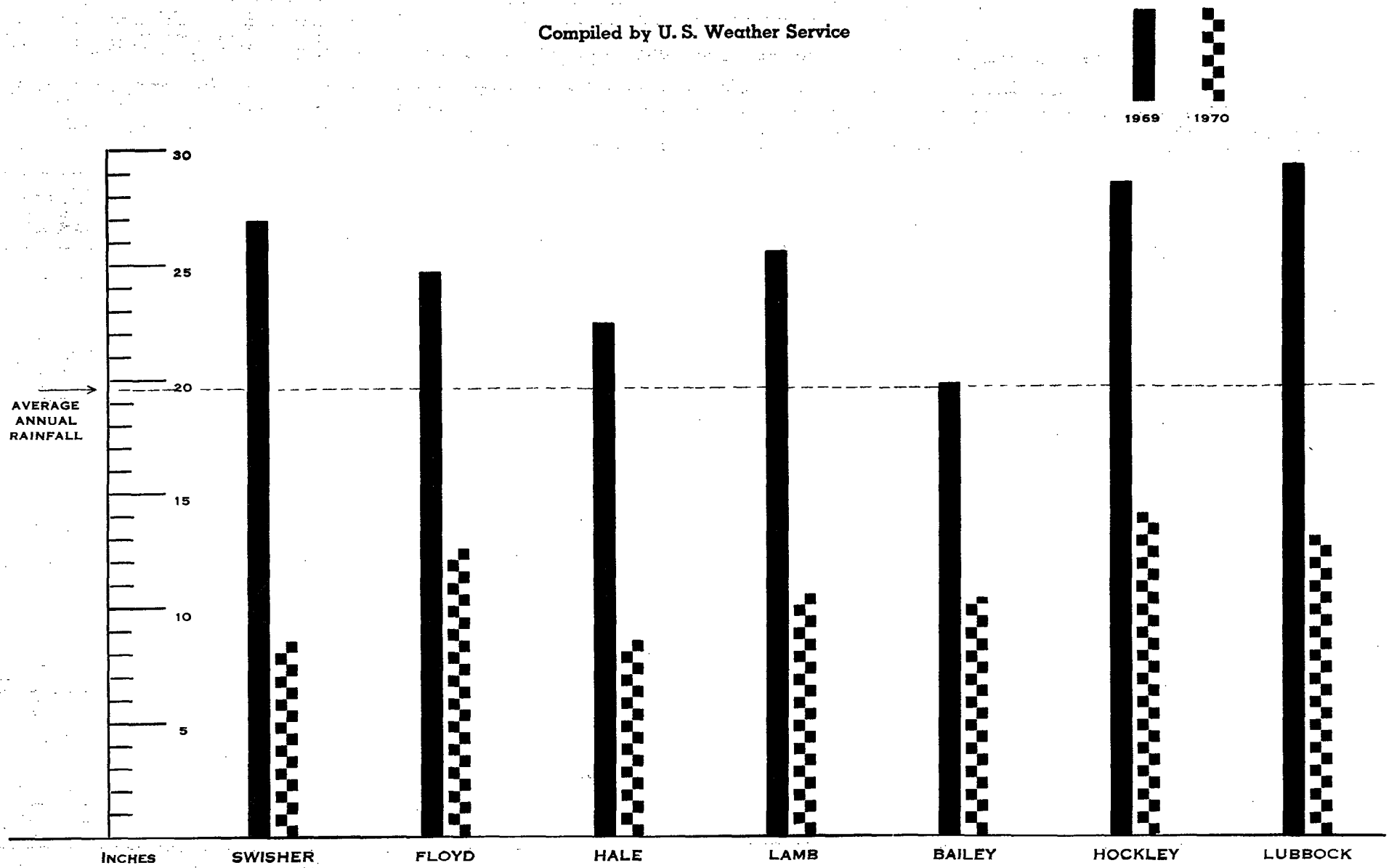
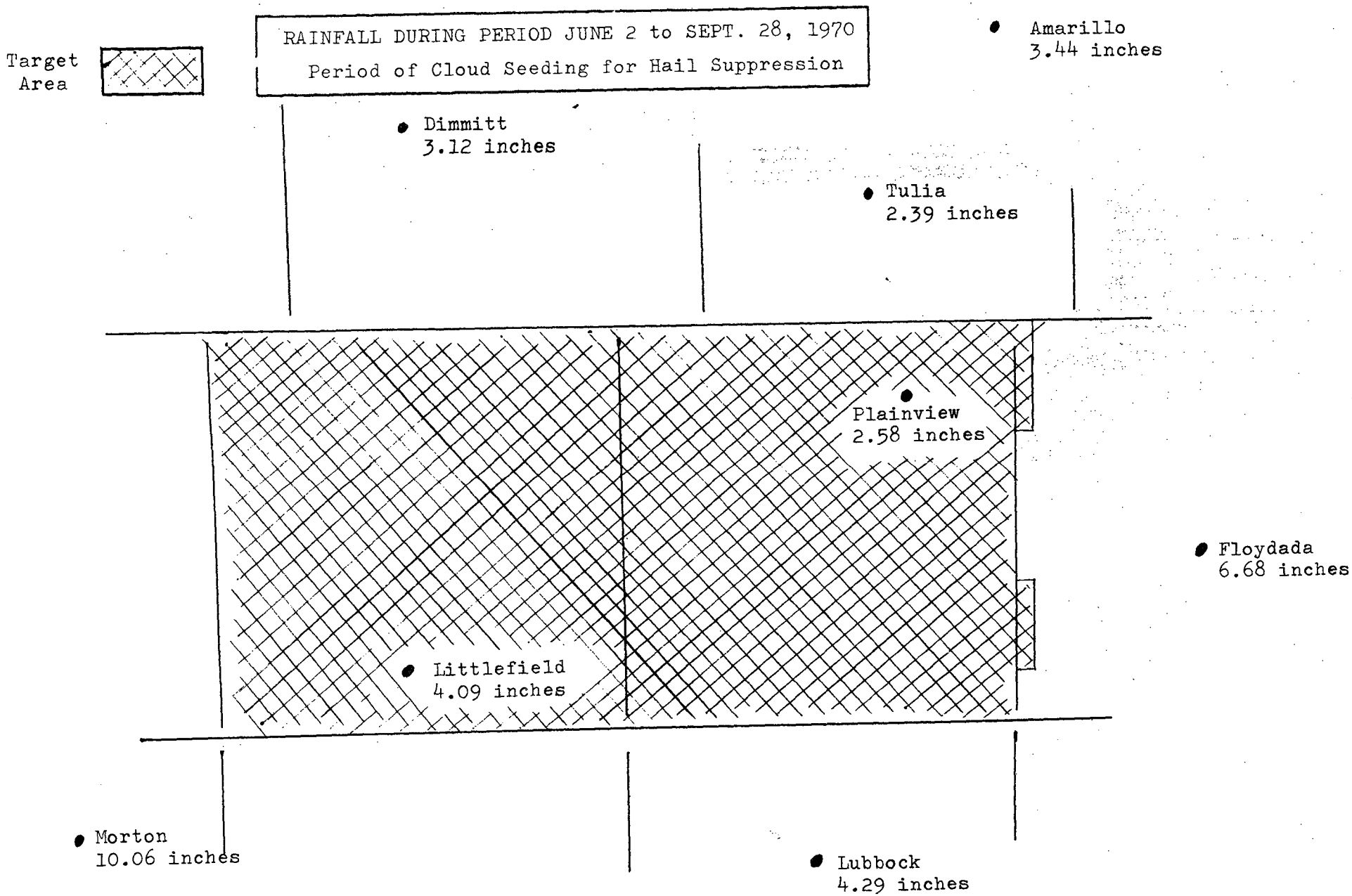


Figure 3



Rainfall figures compiled by Statistical Reporting Service, USDA

Figure 4

SAN ANGELO CUMULUS PROJECT

Meteorology Research, Inc. of Altadena, California, is conducting a 3-year weather modification research project under a subcontract with the Texas Water Development Board (TWDB). This project is funded by the Bureau of Reclamation (BuRec) in the amount of $850,000 through a contract awarded to the TWDB. Expenditures of $241,000 (including $41,000 for Operation T-Drop) have been authorized through June 30, 1971. The area of operation is "vicinity of San Angelo, Texas, within the area bounded by San Angelo, northward to Tennyson, then northwestward to Hyman, southwestward to Rankin, southeastward to El Dorado, and northward to San Angelo. The two goals of this project are to increase precipitation by any means deemed appropriate and to perform sophisticated experiments with warm clouds in search of an operational means of increasing the precipitation from these clouds.

The San Angelo Cumulus Project is a three-year research program designed to develop practical procedures for beneficial precipitation management in Texas and other Southern Plains and Gulf States areas. Included in these procedures will be ice-phase seeding techniques developed elsewhere and refined for application in the project area, and warm cloud techniques developed within the project.

San Angelo was chosen as the base of operations for the program because of the existence of the Twin Buttes and San Angelo reservoirs which provide storage capabilities for any additional water that might be produced, along with a vital need for such water and a rich source of appropriate clouds for experimentation.

The approach to the project is one of systems analysis in which all aspects of the problem are considered. In this case these aspects include: scientific pursuits involving numerical model development, detailed field observations, and extensive data analysis and evaluation; engineering aspects incorporating hydrologic, precipitation management and decision-making considerations; and sociological factors including ecological monitoring and an extensive public relations effort.

The goals of the program can be subdivided into ice-phase and warm-cloud seeding objectives. Each of these, in turn, can be further subdivided into small and large cloud components. Thus, four distinct problem areas are identified; isolated cold clouds, cold cloud systems, small warm clouds, and large warm clouds. Past research in each of these areas provides some basis for the current program.

The field program for this year was operational from 3 May to 31 July 1971. Fig. 5 shows the location of the project instrumentation. The primary target area for the seeding is the drainage basin for the Twin Buttes Reservoir. The secondary target is the drainage basin for the San Angelo Reservoir. This reservoir is of second priority because when the North Concho River is dry, as it was last summer, little runoff

reaches the reservoir from the drainage area of the river within the target area. Figure 6 shows the experimental procedure for large clouds.

SAN ANGELO EMERGENCY OPERATIONS

The Bureau of Reclamation made available $41,000 during the month of June to expand the area of the San Angelo Cumulus Project eastward to the Colorado River, southward to the Balcones Escarpment and westward to the Pecos River.

SAN ANTONIO AREA EMERGENCY OPERATIONS

The Bureau of Reclamation, Air Force and TWDB were involved in an emergency weather modification operation in an area west of the Colorado River to the Rio Grande and from the Balcones Escarpment south to the Gulf of Mexico.

The Bureau of Reclamation directed the program, the Air Force provided personnel and aircraft, and the TWDB provided liaison with the local people.

The cost of this program, which concluded June 30, is not yet known, however, the BuRec and Air Force are providing all of the monies.

Official word was received on Friday, June 4, 1971 that the Texas Drought Relief Operation (T-Drop), the TWDB - BuRec - U.S. Air Force part of the operation would begin on June 5 at Kelly AFB, San Antonio.

The T-Drop area was divided into two zones. The northern part of the area was under the operational control of Meteorology Research, Incorporated as an extension of the San Angelo Cumulus Project. Two additional aircraft, a converted B-23 from the University of Washington, and a converted B-26 from the University of Nevada were obtained by the BuRec under contract for seeding in the northern T-Drop zone, and a BuRec radar was stationed at Junction, Texas to provide radar coverage for the enlarged seeding zone. Both silver iodide and hygroscopic seeding materials, using salt or an ammonium nitrate - urea mixture, were dispensed by these converted aircraft in the northern zone, depending on the type of cloud present.

The southern part of the T-Drop area was under the direction of the BuRec. The USAF furnished two WC-130 aircraft, pyrotechnics, and the facilities of Kelly Air Force Base. These USAF aircraft were equipped for silver iodide seeding only. Official results of this month-long emergency drought relief cloud seeding operation are being analyzed and should be available early in 1972.

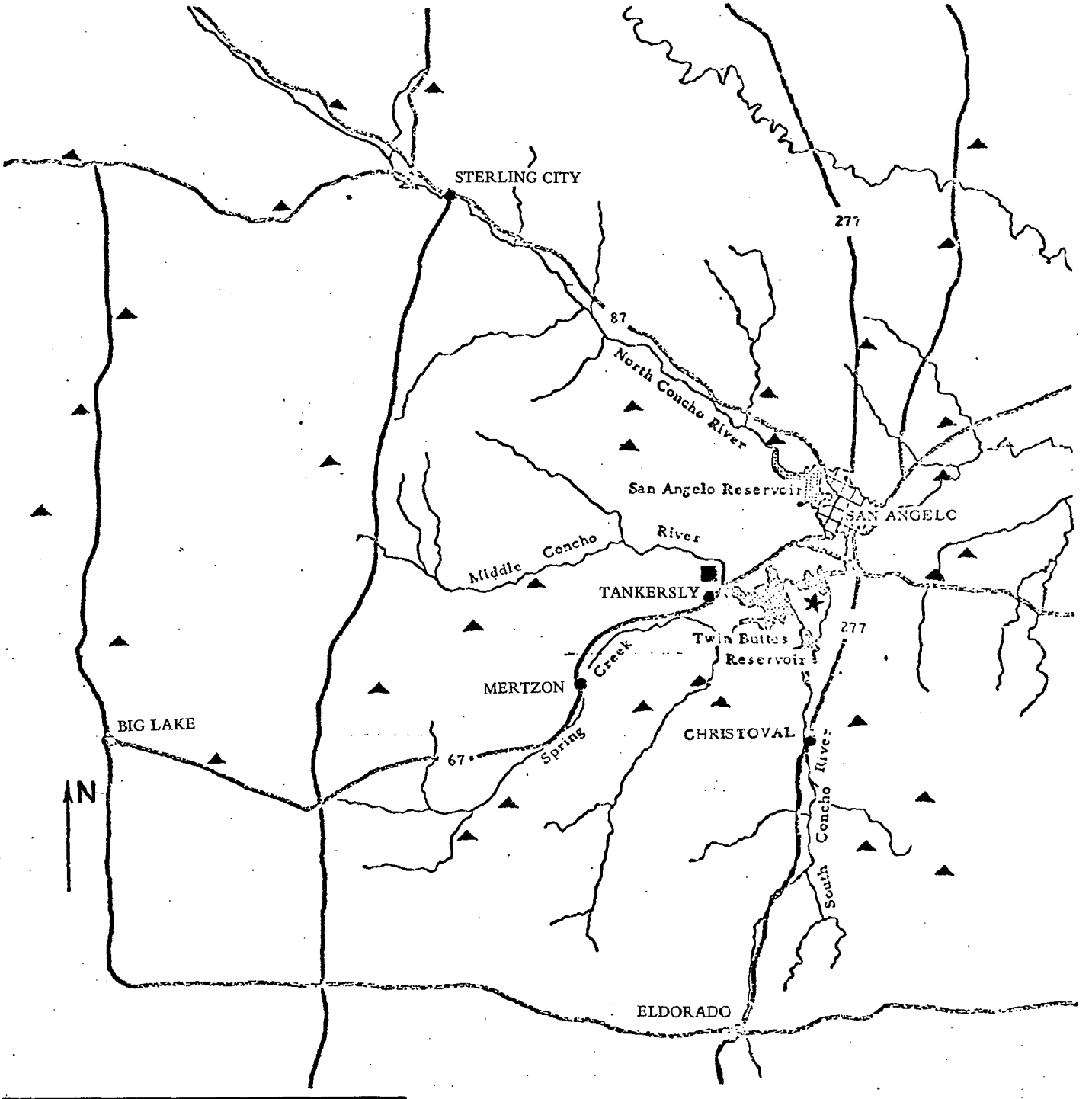


Fig. 5. SAN ANGELO CUMULUS PROJECT AREA

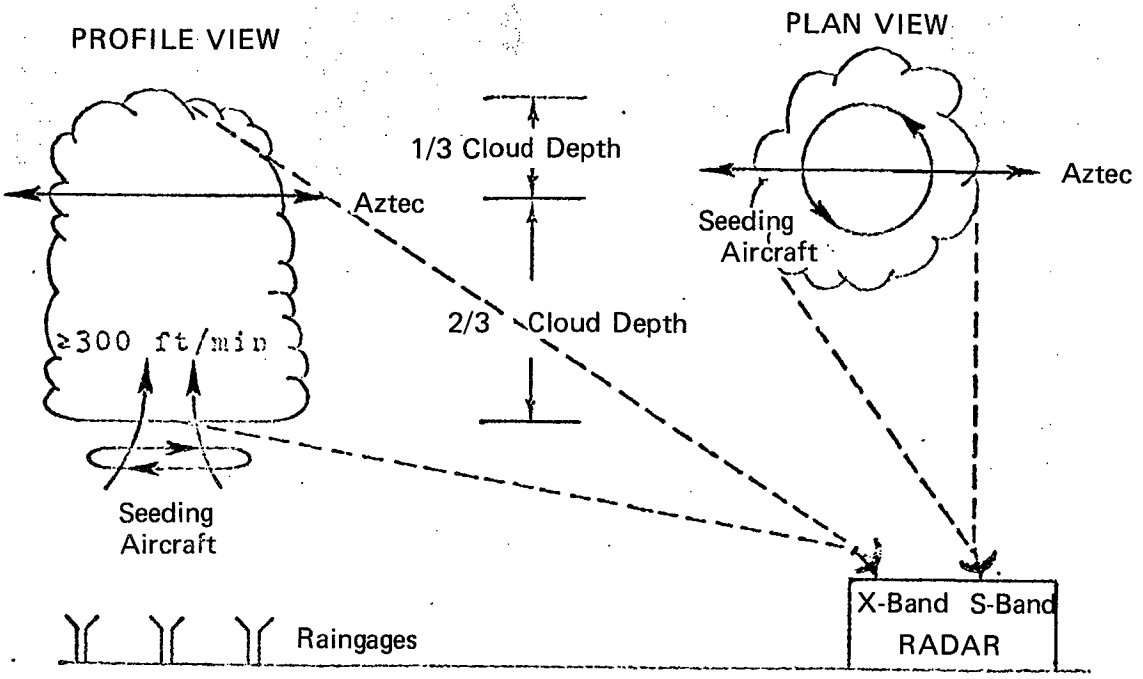


Fig. 6. EXPERIMENTAL PROCEDURE

ILLEGAL CLOUD-SEEDING OPERATIONS

One illegal unlicensed and unpermitted operation was allegedly carried out by an out-of-State practitioner during the early months of the year. A coke-fired ground-based generator was used, with silver iodide being the principal seeding agent used. Coke (or charcoal) was impregnated with silver iodide and other "chemicals." The "generator" was fired and a forced draft was provided by a 12-volt fan. The one unit observed in operation was mounted in a truck bed and driven along public roads while in operation. The practitioner had promised to produce five inches of rain in a period of about five weeks with the proviso in his contract that he would continue in operation past the deadline in the event five inches of rain were not produced.

This operator was presented with application forms to complete and advised of the State law regarding licenses. He completed the forms, paid the fee, and made application for a license. The Weather Modification Advisory Committee examined his credentials and unanimously rejected his application for a license. He was advised of the inadequacy of his credentials and his license fee was refunded. He never produced any rain which caused the total rainfall for the period to exceed the climatological normal. In fact, this area received only a little over half the normal amount of rain during this time. He returned to his home state shortly after being formally notified that continued operation without a license would be in violation of Texas law.

A second illegal unlicensed and unpermitted operation was reportedly carried out just inside Texas across the border from Oklahoma. The target for this operation was in Oklahoma but the ground-based generator was positioned in Texas, upwind (for the season) from the Oklahoma target. This out-of-state operator promised to produce a stipulated amount of rainfall in a given amount of time. Newspaper accounts say that he returned to his home state without achieving his goal or receiving pay for his efforts. This operation was conducted in the heat of the summer in an area of extreme drought according to the Palmer Drought Index.

HOW TO SEED CUMULUS CLOUDS

by

Pierre St.-Amand and Shelden D. Elliott, Jr.

Naval Weapons Center
China Lake, California 93555

ABSTRACT

Techniques useful for seeding cumulus clouds, with glacogenic nuclei, for rain augmentation are discussed in detail.

Clouds are seeded by emplacement of glacogenic nuclei in updrafts at the top of unsheared clouds at the warmest temperature at which the nucleant is effective. Sheared clouds are seeded in updrafts on the upshear side of sheared clouds at the same temperature level.

Usage rates, aircraft handling procedures and operational considerations are discussed.

HOW TO SEED CUMULUS CLOUDS

In the preceding papers of this series, the background for understanding the action of glacogenic seeding agents was set forth in some detail. We will now consider the seeding of cumulus clouds giving the techniques developed and used by the NWC group in the Gromet series of drought relief programs. There are other methods in use by other groups. We will not review these in detail but in not doing so we do not wish to appear to have neglected them nor to imply that they may not be equally useful. We do feel that the methods set down herein are useful and valuable and represent a fruitful method of proceeding. The methods can certainly be improved upon and no doubt will undergo considerable change with the passage of time.

The approach to this problem was largely intuitive, based upon observation of the natural modes of cloud growth as deduced by looking at them and flying through and around them. It was reasoned that if one could divine the movement of the air and then acted upon the clouds in a manner that tended to augment the natural proclivities and processes, that the cloud could be made to do more of the same. This technique has worked well.

In all our work we have drawn heavily upon the help and advice of others, shamelessly adopting their techniques and ideas as they become available. Indeed, we learned so much from such people as Tommy Henderson, D. Ray Booker, R. Elliott, L. Lee Wilson, Wayland Livingston, Steven Little, J. Donnan, Wally Howell, Ed Berry, David Merrill and others that

it is only polite to acknowlege their contribution to our efforts; properly they should be included as authors in this series, except that they might well not agree with any or all of our conclusions.

Most of the techniques described herein were presented at the Second Annual Conference on Weather Modification at Santa Barbara in April 1970. They have been described in some detail in our report on Gromet II, St.-Amand, Reed, Wright and Elliott, 1969.

Two basic techniques are involved, the first is that of placing glacogenic nuclei in updrafts in or near the tops of clouds, the second, that of putting the material in at cloud base.

NUCLEATION OF CLOUDS

A nucleant for seeding clouds must be placed in the right spot at the right time in accordance with its known, or reasonably anticipated, mode of reaction. The reader is referred to our previous discussions (St.-Amand, et al., 1971a, b, c, d, e) in the WMA Journal for details of the behavior of various types of nuclei. A short recapitulation is given here.

A nucleant should undergo few chemical changes in the presence of water. To this end, the use of silver iodide as opposed to that of a complex is important. The solubility of the material is a paramount consideration when the agent must spend a period of time, long compared to its solution time, in the presence of liquid water or water vapor.

The solubility factor plays an important role in the type of cloud to be seeded. Complexes of silver iodide and alkali iodides or lead iodide and oxyiodides will cause freezing of smaller cloud droplets but be relatively ineffective in freezing of precipitation size particles and larger drops, because of the rapidity of solution of the aerosol particles. Large enough particles of relatively pure silver iodide will cause freezing of both small and large droplets. The work on solubility presented by St.-Amand, et al., (1971e) and by Mathews, et al., 1971, 1972, gives the minimum effective size of AgI aerosol particles for droplets of a given size.

The freezing of larger droplets is usually desirable because the rate of release of heat of fusion is faster than if only the smaller droplets are frozen. Further, the velocity differential of the larger drops enhances the rate of accretion of nuclei and other drops. Thus if cumulus seeding is the objective one should use a nucleant generator that produces 10^{13} nuclei per gram. If seeding of a supercooled stratus is envisioned, then a generator yielding a larger number of nuclei per gram can be used. A more soluble nucleant will release heat more slowly because only the smallest drops are frozen and growth time of the ice particles and of the cloud is increased. This may sometimes be advantageous in dealing with marginal clouds in which too rapid a growth may

result in destruction of the clouds. On the other hand, reprecipitation of AgI at greater altitudes, due to further cooling may delay the freezing of larger drops.

The maximum temperature at which a nucleant may work is of consequence in that the number of workable clouds increases rapidly with a slight increase in threshold temperature. This is quite valuable under marginal cloud growth conditions in which rainfall increase is most needed. Further, naturally available nuclei increase as the temperature decreases and hence the effects achieved by artificial nucleation become less important and less useful.

In order to influence cloud growth in a time short compared to the lifetime of the clouds, one must add enough nucleant to freeze an appreciable number of droplets. Our paper on contact nucleation, St.-Amand et al., (1971d) shows that when the effects of Smoluchowskian and Brownian collision alone are considered, numerical densities of the nuclei of the order of 10^4 or 10^5 per cubic centimeter will insure nucleation of most droplets in a cubic centimeter of cloud within a few seconds provided the drops are large enough. Smaller amounts may well work but at some point the process is too slow to affect the growth cycle of the cloud.

In seeding cumulus clouds, we try to seed only the updrafts because the droplets therein are larger, the liquid water content higher and the relative humidity is higher. Thus because the probability of both collisional and diffusional growth of ice is increased, the release rate of heat is increased. Dynamically, the updrafts are the place to seed because release of heat will accentuate an updraft. The cloud exists because the updraft is lifting water vapor, hence an addition to the updraft velocity and diameter will in general cause more cloud growth. Downdrafts are important to cloud development and would be decreased if freezing were to take place therein. While occasionally a downdraft can be changed to an updraft, it can only be done with an enormous number of nuclei because of the small droplet size and lower liquid water content usually found in downdrafts may well require 10^3 or 10^4 times the numerical density of the aerosol needed to nucleate an updraft (St.-Amand, et al., 1971d).

A NATURAL TROPICAL RAIN PROCESS

An important process in the production of rainfall from cumulus clouds in the tropics and probably elsewhere can be frequently observed.

During periods in which a strong temperature inversion, such as the marine subsidence inversion or the tradewind inversion exists, clouds frequently grow to the top of the inversion and only occasional turrets succeed in rising to greater heights. While rising, the tops of the turrets have a fine, hard white appearance. This is due to an abundance

of relatively small drops that scatter the light and preclude seeing very far into the cloud. As the turret passes the inversion it rises first through slightly warmer air and then into a colder, much drier region.

Once the turret reaches it apex, the smaller structure on the surface begins to disappear and it develops a smoother darker appearance. After a time the small droplets begin to evaporate, the larger droplets lose some mass and the air begins to cool. The appearance then changes to a grayish striated mass in which lines or streaks of droplets can be seen, because the smaller drops are gone and the tower becomes more transparent. This is followed by a change to the appearance of plucked cotton and the turret now begins to fall back into the mass beneath, which then darkens just below the descending turret and a shower develops below the collapsing portion of the cloud.

The falling drops grow by condensation for a short while because they are colder and by collision with the underlying smaller, more slowly falling droplets. No ice is necessary to this process and indeed the Bergeron-Findeisen process plays little or no role in clouds over most of the tropics because these clouds are relatively ice free at altitudes to 30,000 feet.

The techniques of seeding described herein accentuate this natural process by causing cloud growth, with subsequent collapse, at least in the smaller clouds. In many respects, effective seeding of a marginal convective cloud is akin to bringing a banked furnace to life. With the foregoing in mind, we will proceed to discuss the seeding of cumulus clouds.

CLOUD SEEDING TECHNIQUES

Seeding of cold topped cumulus clouds as practiced by our group involves locating updrafts in clouds and releasing carefully-guaged small amounts of seeding material therein. The seeding agent causes supercooled water to freeze, causes growth of ice on the nuclei by diffusion of vapor and hence releases heat of fusion and sets in march a more rapid condensation of water on the ice thus produced than is possible on the liquid droplets, with of course a concommitant release of heat of condensation at a greater rate. Clouds appear to operate at near equilibrium conditions and even a small change in heat release causes a change in updraft velocity. Heating makes the air more buoyant and the updraft area and velocity is increased, sucking in more air from below and causing increased condensation throughout the ascending column with a resultant increase in rate of heating by condensational heat release in the lower parts of the cloud.

A detailed analysis of the seeding process was presented by St.-Amand and Finnegan (1970) at the Santa Barbara meetings.

The techniques described herein are not difficult; the proper procedures can be learned by an instrument-rated pilot in about 4 hours and can be developed to a high degree of skill after a week's practice. Seeding is based on visual observation of the clouds, interpretation of the airflow in and around the clouds, and placement of seeding charges so that the processes causing cloud growth are enhanced.

Timing and restraint are important. Growing towers, recognizable by their hard, cauliflower-like appearance, should ideally be seeded just as they pass the warmest level at which the nucleant used will work before the towers have begun to stabilize in altitude or fall back. Restraint is necessary to preclude too rapid localized growth, which causes spindly towers to break off at midcloud level and separate, and also to prevent overseeding to such an extent that an outflow shield develops.

The most productive technique is to cause neighboring turrets to join in a cloud and then to cause neighboring clouds to join, thereby increasing the areal extent while confining vertical growth to no more than 28,000 or 30,000 feet of altitude. As such complexes develop, new turrets appear, especially upwind, or upshear, and on the flanks of the mass, which are ideal candidates for further treatment.

The procedure of seeding updrafts of clouds minimizes the energy dissipated in turbulence, and in changing momentum, so that only delicate treatment is necessary. It is unproductive of rain to seed the whole cloud top because such overseeding induces too rapid growth which results in disturbing the internal organization of the cloud and the air currents sustaining it. Further it seems to us as if the preservation and health of the downdrafts are of importance in permitting cloud growth; causing water in the downdrafts to release heat would impede the downdrafts and cause a stagnation of rising air above the updrafts thereby impeding development of the updrafts. The most striking aspect of a successfully seeded cloud is, not its vertical growth or rapidity of development, but its general increase in overall bulk.

EFFECTS OF WIND SHEAR

Shear in the wind field has an enormous effect on the results of seeding. We use slightly different techniques for seeding under different conditions of vertical shear. Any possible variation of wind speed with altitude may occur and the seeder must be aware of the shear conditions and be prepared to take advantage of them. For purposes of these discussions we will consider three arbitrary categories often found in air mass clouds. We will call them Class A, B, and C (Fig. 1).

Class A Clouds

In Class A clouds, wind shear is low or nonexistent, say 5 or 10 knots between the ground and the freezing level.

Generally, Class A clouds occur as isolated towers or clumps of towers. Our approach is to seed them if they are more than 1 n mi in diameter, although smaller towers can frequently be seeded effectively.

Seeding is accomplished by flying just over the top or by penetation at the lowest level at which the nucleant can be expected to work, for relatively pure AgI in adequately large particles, such as is produced by the pyrotechnic LW-83, the -3^{o} to -4^{o} level is adequate, St.-Amand, et al. (1971a). For most complexes a higher level is needed. For AgI-3KI complexes (Burkardt, et al. 1970) and lead oxyiodides, good results may be obtained at the -1^{o}C level, and although growth is much slower, it is frequently quite effective.

The penetration technique is to approach the cloud at a safe penetration airspeed, fast enough to minimize downwash and the danger of high speed stalls but slow enough to avoid subjecting the aircraft to undue accelerations; trim and power should be set for level flight while well away from the cloud and not changed thereafter. From then on, one flies toward the most vigorous rising portion of the turret, carefully maintaining the same attitude set up after power adjustment, and noting compass heading.

Before entry, beginning at a distance of one to one and a half cloud radii, a downdraft is usually observed. As the cloud is approached, the individual turbulent rolls in the cloud are seen to move upward, whereas the details in the rolls are seen to move down. Upon entry turbulence becomes noticeable and the downdraft, found outside, changes to a near neutral condition a short distance inside. As penetration continues turbulence increases until a hard upward jar is felt and a sustained updraft is encountered. After a few seconds, if the updraft is sustained, one cartridge is fired. About this time one notices that the wind screen has begun to accrete liquid water because the droplets are now large enough to strike the wind screen instead of being deflected up and around it. The aircraft is now in the updraft core. If the liquid water continues high for at least ten seconds, a second shot can be fired. Turbulence in the updraft core is much lighter than in the more peripheral parts of the cloud. It is wise to continue to fly constant attitude quite rigorously in order to be sure of identifying the updraft core; this will also minimize discomfort due to turbulence. After a few seconds more, depending on cloud size and aircraft speed, the liquid water and updraft decrease, a hard downward jar is felt and the updraft rapidly dies out being replaced by near neutral conditions with increased turbulence. Upon breakout a downdraft is again noted. The sequence of events is shown in Fig. 2 and in Fig. 3. Figure 3 is a copy of a recording of conditions on a penetration made in a Class A cloud in the Philippines.

The forward speed of the aircraft carries the cartridges forward for some distance into the updraft core. At 200 knots, the round carries forward 500 feet or less in the first 1500 ft of fall and thereafter falls essentially vertically. It is therefore necessary to release just before the updraft core is reached. The liquid water ranges from 0.5 g/m^3 or less outside the updraft core to 0.5 g/m^3 and in extreme cases as high as 5 g/m in the updraft core. If the liquid water content of the core is less than 1.0 g/m^3 or the updraft less than, say, 200 feet/min seeding with pure AgI rarely results in rapid cloud growth.

Ordinarily, upon exit the pilot flies outbound for one minute and then executes a 90^0 - 270^0 procedure reversal so that he can look back at the seeded column. If this is done carefully, there is little difficulty in identifying the seeded tower. Usually the volume of the seeded tower above the freezing level doubles in five minutes after seeding. If growth is noted, the tower is not seeded again until considerable growth has occurred, or until adventitious towers at the side, or neighboring towers begin to develop.

If the turret is carefully repenetrated there is usually a noticeable increase in turbulence, liquid water content and updraft velocity. Also large particles of graupel are noticed striking and sticking to the windshield, water running off the darker ice particles as they slide slowly along the windscreen.

We have repeatedly attempted to measure ice nuclei in the towers and failed, probably because of rapid uptake of the nuclei by droplets or by growth of ice embryos thereon. Nuclei are always found in clear air tests or around the periphery of rainshafts at the base of seeded clouds because there they have been freed by evaporation of some of the smaller drops. Indeed, detection of substantial numbers of nuclei in the seeded region would imply overseeding or the choice of an ineffective nucleant.

In the Philippines, for example, small, seeded, single turrets at least 1 n mi in diameter grew rapidly-- at rates as great as 1,000 to 2,000 feet per minute, and increased visibly in diameter. The growth continued for a few minutes, sometimes as much as ten to twenty minutes, and the appearance of the upper part changed from a hard cauliflower-like white mass to a light gray whispy condition with the appearance of plucked cotton. Following a period of quiescence, the uplifted portion dropped back into the mass beneath and the portion below developed a dark appearance. At first a light rain would begin to fall and then a rain shower, producing about 100 to 500 acre feet of rain would continue for 15 to 20 minutes with an intensity of 1 to 2 inches per hour. Frequently, the center of the cloud would punch out completely after a shower and leave a disorganized ring of cloud around the seeded area.

In general, single towers, properly seeded, regenerate, usually slightly upwind of the lower portion. Nearby towers begin to grow following seeded growth of a neighbor. The mechanism for this is not

clear, but it seems as if the enhanced downdraft and cold air around the growing tower lifts the lower moist air like a micro cold front. More likely, a counter rotating vertical cell is formed beside the cloud and the downdraft from the seeded cloud enhanced the downdraft around neighboring clouds, thus encouraging their updrafts (Fig. 4).

After one tower is seeded, it is usually left to grow by itself and attention is given to nearby towers. The more vigorous are selected and the smaller ones left alone. Seeding is done in such a way as to consolidate the towers of one cloud (sometimes called feeders) into a coherent mass. New towers around the edge of the mass are seeded, the central part left alone, and when nearby masses are made to grow thusly, they can be consolidated into one big cloud. An already large cloud, with good internal development is only seeded peripherally.

Once a sustained system is established, the larger clouds frequently incorporate the smaller clouds nearby. These latter are sucked in from the sides or from below along with whatever scud may be present. Occasionally a clear aureole develops around a family of towers that have been consolidated into a vigorous mass. If observed at the critical moment, this process is strikingly reminiscent of what happens when one applies a vacuum-cleaner nozzle to a dusty floor.

As development continues and the system becomes self-sustaining, the cloud base begins to lower and widespread rain develops. Care is taken not to seed too much, but to try to bring the growth to the 25,000 to 28,000 foot level only. If seeding is continued in the same places or into clouds already growing vigorously, or at levels above, say, $-7^{o}C$, a cumulonimbus cloud may form, especially if a strong windshear exists at higher levels. Development of a cumulonimbus leads to high winds on the ground, excessively heavy rain over a small area and loss of a great deal of water in an outflow shield that throws a shadow over nearby clouds and inhibits their growth. Even with care, an occasional seeded cloud develops CB status, especially if the cloud is growing through a temperature inversion with a free convective regime above. Tops in excess of 60,000 feet have developed in the Philippines in this way, following seeding. Although thrilling and spectacular, this is undesirable when increased net rainfall is the object. In the presence of such activity cloud growth is frequently suppressed to distances of 50 n mi up and downwind.

Extensive experience has shown that, in low wind fields, ammunition expenditure in excess of 8 rounds per hour does not result in more rain and usually results in deteriorated rainfall productivity. Timing is extremely important in that one should arrive at the seeding point while the cloud is still growing, or at least before evaporation of material from the top has progressed to the point where the cloud is about to begin descent. Such clouds can occasionally be rejuvenated, but the prognosis is generally poor. Similarly, seeding puffy masses projecting from larger clouds with no substantial amount of cloud below them is fruitless.

Seeding should be confined to updrafts because it is more effective in that slight supersaturations, larger drops and higher liquid water contents exist there than elsewhere in the cloud. These insure more rapid activation of nuclei by diffusion and faster heat release because of more rapid conversion of water to ice by contact nucleation of drops.

Seeding in downdrafts should be meticulously avoided. The nuclei are not so active under the conditions of subsaturation; the liquid water content is less than the updrafts and the seeding material is soon carried downward below the freezing level, where ice cannot form at all.

There are dynamic reasons for seeding an updraft. It already has some upward momentum and is embedded in a circualtion pattern associated with its rise. Seeding a downdraft tends to inhibit an already established circulation pattern that in itself may help the cloud activity by removal of air that would if left to stagnate, impede the updraft.

For example, seeding of isolated towers with a fusee, by flying around the periphery of a tower often results in rapid disappearance of the cloud.

Seeding for rainfall augmentation must always be done so as to aid cloud development by emphasizing the larger scale features of the circulation and minimizing activity that would lead to dissipation of energy in small scale turbulence.

Tropical, or rather maritime, clouds growing in a humid, environment relatively free of hygroscopic nuclei are easier to seed than are continental type clouds. Rainfall is more rapid in its development and ammunition usage is less. In any type of cloud the usage rate is best determined by cut and try: start with one and if that is not enough go back and add more. It is not necessary to try to convert the whole cloud top to ice and is probably not desirable even it it could be done. Effective timing may often be achieved by alternate seeding of two or more nearby, but not immediately adjacent, clouds.

Class B Clouds

Class B clouds are those subjected to a wind shear in which the wind velocity increases with altitude, without much change in direction. Class B clouds lean with the wind because as air rises inside the cloud it is carried along by the wind and because the velocity is greater aloft, the highest parts are displaced downwind relative to the lower parts. Class B clouds usually have an updraft, even outside the cloud along the upshear side, with downdrafts along the sides and behind. The air appears to divide around the cloud and descend as it passes it.

Seeding of Class B clouds is similar to that of the Class A clouds (Fig. 5). In this case, however, seeding is not done in the exact center, but on the forward or upwind front of the cloud, called by some the upshear side.

The technique is to emplace the seeding cartridge in the upshear edge of the upwind most turret that reaches an altitude suitable for the nucleant to work. It is desirable to seed where total vertical cloud depth below seeding is greatest. Penetration on isolated turrets can be in any direction, but on larger clouds, prudence dictates entry at right angles to the wind shear, or penetration in a turn into the front portion only.

If one studies the natural evolution of clouds in a shear environment, it will be observed that new turrets appear and evolve progressively upwind, at intervals of roughly five minutes and one kilometer. If a given tower is seeded just as it reaches maturity, the next pass should be made, not on the original tower, but on the next one upwind. With ideal timing, each new tower is "caught" just as it reaches seeding level. Frequently a plurality of such rows will grow abreast, and two or more towers can be hit in each pass. In larger masses, new growth will also appear on the flanks and can be suitably treated. In this way, considerable "steering" of cloud growth can be achieved.

Class B clouds can thus be made to grow upwind and crosswind, but rarely downwind. Large scale lateral growth is frequently easy to bring about. Isolated clouds of orographic origin can be joined together to make a lineal array. After a few hours, however, such arrangements usually develop into one or more isolated cumulonimbus clouds that dominate the scene.

While successful seeding of leaning clouds requires a slightly larger cloud to begin with than in the case of vertical towers, the leaning towers can be made to produce abundant rain. Care should be taken to prevent development of cumulonimbus clouds that can result in a narrow zone of very heavy rain and increased wind.

Well developed cunulonimbus in a sheared regime can sometimes be cut off by heavy seeding in the main trunk. Penetration is at right angles to the wind shear, and a seeding unit is dropped every 5 seconds. Excessively rapid growth results; the central column narrows and breaks off and the anvil blows away. The underlying cloud collapses and does not immediately regenerate. Updrafts of 2,000 to 4,000 feet per minute have been noted in these shafts, following seeding. It is supposed that the increased vertical flow results in induction of excessive amounts of drier air from the sides and into the base and that subsequent evaporation and cooling cause destruction of the cloud.

Occasionally, one encounters rows of towers arranged along the wind. These are best seeded by proceeding as far upwind as one wishes to develop rain and seeding the nearest tower. The seeded tower grows, and its growth is followed by development and growth of the towers downwind from it. By working back and forth along the system, seeding new shoulders between the clouds, several clouds may be joined into a continuous line.

Seeding rates on leaning clouds is the same or slightly higher than on vertical towers: 10-12 units per hour is a reasonable expenditure rate.

Class C Clouds

With the onset of the southwest monsoon in the Philippines, frequently during trade conditions and commonly on Okinawa, the wind velocity decreases with altitude. The upper part of the cloud moves downwind more slowly than the bottom and the cloud appears to lean into the wind rather than with it. Clouds shaped by this sort of reverse shear are here called Class C Clouds. The situation can be foreseen from pilot balloon observations, forecasts or recognized by noting smoke near the ground, waves on water or cloud drift.

As is the case with Class B Clouds, seeding should be done on the upshear side of the cloud so that coalescence of old cloud and new growth is a maximum. For Class C clouds, the upshear side is the downwind side. Seeding may be done by penetration as in the Class B clouds, Fig. 6, or at the top of a rising tower. Seeding of the downwind most rising tower, that reaches to the temperature level at which the nucleant begins to work is the method of choice.

Classs B clouds can be grown laterally or made to grow and move more rapidly downwind.

FLIGHT PROCEDURES IN CUMULUS PENETRATION

Cumulus clouds are abhorred by most prudent airmen because the dangers involved in penetration of large cumuli are great for a pilot who does not know how to do it. On the other hand, penetration can be done quite safely and without serious difficulty if a few rules of good airmanship are applied.

The difficulty arises in part from attempting a combination of instrument and visual flight. As a pilot approaches a cumulus cloud, he has a tendency to raise the nose, because the visual horizon becomes apparently the cloud top, because the cloud is rising, or because of the downdraft outside the cloud.

This results in excessively slow flight and an excessive angle of attack. Airspeed can be reduced to the point where a high speed stall is possible in turbulence or in a severe updraft. This loss of airspeed is then instinctively compensated for, once in cloud, by adding power and dropping the nose until the rate of climb meter returns to near zero. By this time the aircraft is diving, airspeed is often excessive and heading may be lost.

Attempts to hold altitude can easily lead to wide excursions in airspeed. Too often pilots place primary reliance on the rate of climb meter. This leads to problems because the device has a built-in time lag and often tells one what the aircraft was just doing and not what it is doing at the present moment. The instantaneous rate of climb

indicators are better, but these, too, can lead to unstable conditions if too rigorously followed.

The techniques taught to all instrument rated pilots work well. Upon approach to a cloud, power and trim are set for level flight at the airspeed selected for penetration. In small aircraft, 1.4 to 1.5 times the stall speed for the configuration in which the aircraft is flown is usually used. An aircraft as heavy as a C-130 should fly at least 175 knots indicated, in order to prevent destruction of the smaller towers by excessive downwash. Smaller aircraft do not usually require this precaution. Cessna 210's and 337's can penetrate safely at 120 knots, IAS.

After establishing speed and trim, the pilot proceeds to fly entirely by use of the gyro horizon and gyrocompass carefully maintaining constant altitude. Airspeed is used as a backup and the altimeter and rate of climb are noted but not acted upon. If the gyrohorizon should fail, or in extreme circumstances tumble, reliance should then be placed on the rate of turn indicator, airspeed indicator and gyrocompass; and operation terminated as soon as possible. Attitude, as of level flight, should be rigorously held, ignoring changes in rate of climb and in altitude. Ideally, a constant angle of attack should be held but such instruments are not commonly available.

Response to changes in pitch and bank should be rapid but not over-controlled. If the foregoing procedure is followed, the rate of climb indicator will give a good indication of the velocity of the up and down drafts both inside and outside the cloud, albeit with some time lag. This information is vital to effective seeding.

Changes in altitude during a 2 or 3 minute penetration are not consequential unless the aircraft is flying over mountains or has a poorly functioning oxygen system. Indeed, in a low-shear regime, the aircraft usually exits at near the entry altitude. Icing occurs, but if pitot heat is used, little harm results. The ice evaporates rapidly after the aircraft leaves the cloud. If it does not evaporate, a descent to the -2^{o}C level will usually cause it to fall off, especially in a high speed descent in which aerodynamic heating helps with the melting.

Much turbulence is pilot induced, or at least accentuated. With careful flying in Philippine cumulus, turbulence average 1.5 g where stable conditions are taken as 1.0 g. The extreme, noted in a large cloud, with deliberate aggravation by the pilot was 2.1 g.

The prudent pilot will so plan cloud penetrations that a properly chosen path will bring him clear of other clouds upon flying out. To this end, a curved trajectory is sometimes advisable. A dog-leg approach may aid in observing conditions beyond the target cloud; flying through a small tower into the heart of a CB can be a memorable experience.

Penetrations should be planned so that exit is possible within one to two minutes.

Penetration at altitudes between 8,000 and 16,000 feet lead to the worst turbulence both inside and outside a cloud. This region should be avoided unless cloud physics data are needed.

Penetration along the wind shear should generally be avoided, but penetration in small cumulonimbus can be made safely at right angles to the shear along the upshear side. Usually, a partial penetration is adequate.

Seeding beneath clouds can often be done to good effect, but frequently is not practical due to owing to high terrain and low cloud base. Cloud bases frequently lower following seeding, and it is unwise to be caught in high terrain under these conditions, because the only alternatives are to exit by visual flight rules under marginal conditions of visibility or to attempt an instrument climb out, with no clear idea of which way to go and probably without clearance.

If turbocharged aircraft are used at altitude, it is inadvisable to slow the aircraft below 90 knots because ram air aids the turbo-charger and too slow an airspeed may result in too rich a mixture, causing momentary engine failure. This is disconcerting but not grave, because a restart can be obtained by dropping the nose and leaning the mixture.

Most non-pilots and some pilots have difficulty at first in maintaining orientation following penetration and turning, so that they cannot tell which cloud has been seeded. Smooth flying helps in maintaining orientation. In most cases, a sense of orientation develops rapidly with experience. A trick that permits one to see the exact part of the cloud seeded is to fly out bound for 30 seconds or a minute and then do a 90^{0} - 270^{0} procedure turn at standard rates. If done carefully, one can easily identify the spot seeded and accurately repenetrate if necessary (Fig. 7).

UNDER CLOUD SEEDING

In some localities seeding beneath clouds can be done easily and well. This technique is useful in the Great Plains, where cloud bases are often high and good visibility is present. Isolated clouds respond best to this treatment because one can then tell more easily where to seed.

The technique is to identify the updraft areas and seed in these. Pilotage is more difficult and the seeder must be quite familiar with the rate of climb, power settings and airspeed characteristics of his aircraft.

The chief disadvantage is that he cannot select targets carefully enough so that he can systematically grow new turrets into the cloud mass and encourage peripheral growth and coalescence of clouds. Once beneath the clouds he has difficulty in assessing the rate of growth, conditions at cloud top and the degree of glaciation. It is all too easy to overdo an already large cloud, with consequent reduction in rainfall by development of a heavy outflow shield or perhaps by development of an unnecessary cumulonimbus that brings high winds and overly heavy rain.

Notwithstanding the above arguments, the method has advantages in that less sophisticated aircraft are needed. Cloud base seeding techniques have been tested for us by Weather Science, Inc. (Sutherland, et al., 1971). The results indicate that it is possible to double the rainfall from single clouds by this approach.

Some attention has to be given to the nucleant used for subcloud seeding. Pyrotechnic fusees producing relatively pure AgI, and little else, in the particle size range of 0.05 to 0.1 microns are required in order to give particles large enough to preclude solution in the relatively warm droplets found below the freezing level. The long residence time of the AgI in this inhospitable environment assures solution of a large fraction of the smaller particles.

The same caveats apply to seeding from the ground. The advantages of using relatively insoluble, large particles of AgI may be seen by comparing the more recent work by Elliott, et al., 1971, at Santa Barbara with the earlier work at the same site using a relatively soluble AgI-NaI complex.

FACTORS AFFECTING SEEDING SUCCESS

High Wind Shear: If the wind shear is too severe, or if, in the case of an orographic cloud, the wind is too strong, seeding may not result in as much rain as from the same size cloud as it would in the case of lower wind shear.

Weak mechanically sustained clouds in a low wind shear regime topped by a region of high shear, say 20 knots, or more in a few thousand feet frequently grow into the new regime only to be swept away with the base rising rapidly with little or no precipitation. This condition has been observed in the Sierra Nevada of California, Fig. 8.

DESTRUCTION BY TOO RAPID OR EXCESSIVE GROWTH

If a marginally narrow cloud be seeded too enthusiastically, it is not uncommon for the cloud to "kneck" down at mid-cloud level and for the

top to pull off and drift away with subsequent collapse of the lower part, which may or may not regenerate, Fig. 9. By careful seeding using lead oxyiodides or complexes of KI-AgI so that only the smaller drops are frozen, clouds as narrow as a few hundred meters can sometimes be effectively sustained and grown into larger masses. Unless they can be merged with nearby clouds, however, the prognosis is poor. This technique works well in developing cumulus growth in marginally stable stratocumulus decks.

A more interesting type of cloud destruction of the same class was observed at sea off Okinawa. The details are shown in Fig. 10. A well established marine inversion at 2,000 feet had trapped a good bit of air pollution and haze beneath it with only occasional scud at the top. Out of this were growing a line of cumulus congestus with vigorous development to 18,000 feet. Observations of the cloud growth revealed that without seeding the clouds grew one at a time to about 20,000 feet, the marine inversion upwind decreased in height to a few hundred feet and eventually disappeared for a mile or two upwind. At this time, the cloud base began to rise rapidly. Eventually the base rose to about 16,000 feet and the cloud formed an elongated stratus deck and drifted away. Seeding of two of these clouds resulted in identical behavior, but in a shorter time span. The ultimate heights were a few thousand feet greater.

What appeared to be happening was that upon increased indraft that the clouds used up moist air from the lower levels faster than it could be replaced from below the inversion and colder, drier air from upwind and above was sucked down and into the cloud, eventually to the point where, from decreased humidity the level of condensation was raised. This process is probably critical to the ultimate growth of most seeded clouds.

LAYERED CLOUDS

Frequently a layer of drier air exists between a lower moist layer and higher moist layer. Under these conditions clouds may grow from the lower layer, through the middle dry layer, thinning out therein and widening again at cloud top as in Figure 9. This situation requires great care to make seeding work. Too much seeding can make these towers separate at midsection. However, slow, careful seeding can make these towers grow.

The strategy that seemed to work best was to go to the middle of a field of such clouds and to seed several of the larger, causing enough growth up and drizzle back down through the drier layer to humidify it. After about an hour of such activity, the middle air would be adequately moistened to permit cloud growth and normal seeding often to a considerable distance from the original area.

Occasionally, moist layers below and aloft with reasonably moist air between, say, at 50 to 60% relative humidity, would form a stratocumulus

deck below and a higher deck above. Seeding of rising towers in the lower mass would result in growth, with the tower penetrating the upper layer. Usually the towers rose above the upper layer and then settled back on the sides and spread out, although sometimes they reached considerable altitude following penetration of the upper moist interface. The overall appearance is that of a bubble fountain fed by a stream from beneath. Figure 11 shows this effect as seen over Luzon. Thin, dense stratus layers over rapidly growing convective cells may be observed to stretch considerably upwards, then rupture as the cell pushes through, rather like poking a finger through a plastic film.

OROGRAPHY

In a low wind regime, due to heating, and upslope flow, clouds tend to form over hills before they form over low lands. Even on generally cloudless days, some orographic clouds worthy of attention form and can be seeded.

In the Philippines such clouds formed almost daily over the Zambales Mountains and Sierra Madre Mingan, the two north-south bounding ranges of the Central Valley of Luzon. When these clouds were seeded vigorously and grew, the development of clouds over the Central Valley appeared to be suppressed (Fig. 12).

A plausible explanation for such cloud suppression might be that, Fig. 12b, the rising air from clouds over the mountains descends again in the central valley, adiabatically heating the air and preventing cloud growth. Under these conditions, waves on Manila Bay and Linquayen Gulf indicated a seaward drift of air outward from the valley to the north and south.

If on the other hand, one waited until some clouds had formed over the valley, and then seeded those, an influx of air was noted, and a sea breeze front, consisting of a line of clouds across the valley, gradually formed some 10 or 20 miles inland. Once these were worked, the whole valley began to develop cloudiness, and a second sea breeze front began to form north of Manila Bay. Evidently, the circulation pattern was one of uplift over the Valley, Fig. 12c, with replacement from the sea.

AIR POLLUTION

While some condensation nuclei are needed in order to initiate cloud formation, excessive amounts appear to cause clouds to develop with more small droplets and reduced liquid water content.

Rainmaking in a marine, or tropical environment with clear air is relatively easy. Ammunition usage rates are comparatively low. In a

continental regime, with polluted air, natural rain falls less easily and it is harder to make clouds grow and rain. Ammunition usage is correspondingly raised, often with uneconomical and disappointing results.

It is our opinion that air pollution is a major cause of the numerous droughts currently endemic over large areas of the world.

OPERATIONAL CONSIDERATIONS

The type of seeding described herein is not the only method that will work and about as many methods exist as do cloud seeders; each in general adhering to his own style, some with astonishing vigor and often lack of insight. We contend that our techniques work well and that they are worth looking at and trying. We have proceeded by the technique of first observing the clouds, trying to understand what they are doing and then attempting to accentuate natural processes where they act in the desired direction. No apology is made for the lack of statistics involved in this semi-instructional note. Not enough resources exist to prove each point by the usual so-called scientific approach. The effects produced are readily apparent and the reader is encouraged to try them. A simple clear-eyed look is well worth a thousand numbers.

The techniques herein described are applicable to many places in the world. Because they will probably be used a good deal in the future, we shall set forth herein a number of operational suggestions that may prove helpful in future operations.

FORECASTS

With rawindsonde and other data available, a capable forecaster can predict cloud formation and location adequately to be of use in planning the day's activities. Although helpful computer models exist, computers are not usually available and are too expensive for routine use; nor are they necessary. The utility of these lies in the future, in developing insight into cloud processes.

All too often reliance is placed upon computerized forecasts based upon sounding data taken miles from the working locality and frequently at the wrong time of day. Clouds, as they form and dissipate soon change their environment, and many of these effects are too localized to be detected on the synoptic scale.

A good forecast will include the possibility of orographic development, even under conditions unfavorable for purely convective growth.

Once the forecast is in hand, aircraft should be launched, even in marginal conditions, to take advantage of any clouds that may be found.

There are usually some that can be worked. Conditions change with place and time and often weather stations do not report clouds, even though they may be seen from the air at a little distance. This is especially true under drought conditions because air pollution often precludes good visibility. Aircraft: Although multiengined, pressurized aircraft are difficult to surpass in terms of comfort, safety and convenience, cloud seeding can be done with much simpler equipment.

At NWC we have used the cheapest single-engine light aircraft available that could reach seeding altitude in a reasonable time. In most cases this is satisfactory and safe enough, but in some situations a multiengine aircraft is preferable.

Any supercharged reciprocating or turbine powered aircraft capable of sustained operation at 25,000 feet will do. A reasonably high cruise speed at altitude and a high rate of climb are important.

The Cessna 210 is a good aircraft for the purpose. Two external seeding racks can be carried, one under each wing, or fusee mounts can be installed aft of the trailing edge. An excellent seeding aircraft is the Cessna 337. This model can be operated on one engine to conserve fuel while waiting for cloud development. Operating costs for the 210 is about $45 per hour, for the 337 about $60 per hour. Any turbocharged light twin of comparable cost is equally satisfactory. One such aircraft can work an area about 100 miles in radius very effectively. Surplus military aircraft are usually not suitable, are too expensive to operate, and difficult to maintain. Reciprocating engines built in the 1940's and 1950's generally cannot operate effectively at altitudes high enough to be useful. They are too complicated and use too much fuel. Jets operate effectively at altitude but usually cannot remain on station long enough and fly so fast that targeting is difficult. Their fuel consumption is inordinately high. Complex aircraft hydraulic systems do not respond well to intermittent use with long periods of idleness.

Careful consideration should be given to aircraft supplies and equipment.

1. Supplemental oxygen should be carried because the usual supplies are marginally adequate. Demand flow oxygen systems are preferred if available, and high quality masks should always be used. Pressurized cabins are now available and are more comfortable, but not necessary.

2. Dual navigation/communication gear is necessary. A distance measuring apparatus is desirable, but is frequently useless in many areas because of lack of ground facilities. If possible, dual automatic direction finders should be installed because many areas have suitable nondirectional beacons whereas they lack other means of navigation. An instrument landing system is desirable. In some areas high frequency communication gear is necessary. Over most of the United States, a

transponder is required for flights at seeding altitudes, but is really not necessary to the flight itself unless radar control from the ground is needed. Most air traffic control radar cannot track a light aircraft for long without a transponder, especially if the plane is of wood or plastic such as a Bellanca or Windecker.

3. Aircraft radar is a convenience and of great use in estimating distance to targets and in judging the effects of seeding. It cannot, at the present state-of-the-art, be easily installed in most single engine aircraft and is usually not used in twins because of cost.

4. Spare parts peculiar to project aircraft should be brought along on foreign operations because while mechanics are usually available, spare parts are often scarce and slow to obtain.

PILOTS

Local pilots who know and are interested in the area can serve well. They should be instrument rated, or at least capable of short periods of instrument flight in turbulence. If possible, after some chalk talks, they should be trained to seed by another pilot familiar with the technique.

EVALUATION

Evaluation of the results may not be required, but it is an important factor and one of the most difficult to carry out. Because seeding projects are generally conducted in dry areas where the need for water production is urgent, there is often little interest in a full-scale statistical experiment. Every aircraft is needed to seed every cloud possible. Randomization to acquire scientific information, so important to American investigators, is generally not favored by local officials, nor indeed is any evaluation process that exceeds 10% of the project cost.

Rainfall measurement is best done by calibrated radars, but these rarely are found in adequate numbers and interpretation methods are still somewhat in dispute. Raingauges are practical but an enormous number are needed. Observation and reporting are expensive.

Carefully kept accurate records of each seeding locality and each cloud seeded is valuable in keeping the record clear and of help in evaluation. One should include date, time, place, type of cartridge fired, altitude, heading and observations of effects. Photography, preferably with a Polaroid type, hand camera, combined with the above log is a help to evaluation and provides an excellent debriefing tool. The

same camera can be used to photograph the aircraft radar scope--if one is available.

The real proof is in benefit to agriculture and irrigation. In many cases, estimates of water yield and runoff can be made but so many variables are at work that one cannot always be sure of the results.

LOCAL PARTICIPATION

It is important to secure the active cooperation of local people at the rainmaking operations. They should be included in the work to as large an extent as practical and their advice should be actively sought and considered. Irrigation, water and power people, and agriculturists are usually hopeful and enthusiastic. The weather people, as a rule, are not as vitally interested and may offer some resistance. A continuous effort to involve them in decision-making processes and evaluation should be undertaken. Providing seminars, reprints of weather modification papers and taking a few local personages along on seeding missions are some ways of insuring productive involvement. However, the people should be chosen with care, such activities limited to good seeding days and the air work confined to mild penetrations because people unaccustomed to such flights get airsick under conditions that an experienced person finds dull.

WATER MANAGEMENT

Often, lack of water points up a less than adequate water management system. It should be emphasized to the recipients of the benefits of cloud seeding, that seeding alone is not adequate to solve problems that were perhaps centuries in the making and that a proper water storage and distribution system is often the real need.

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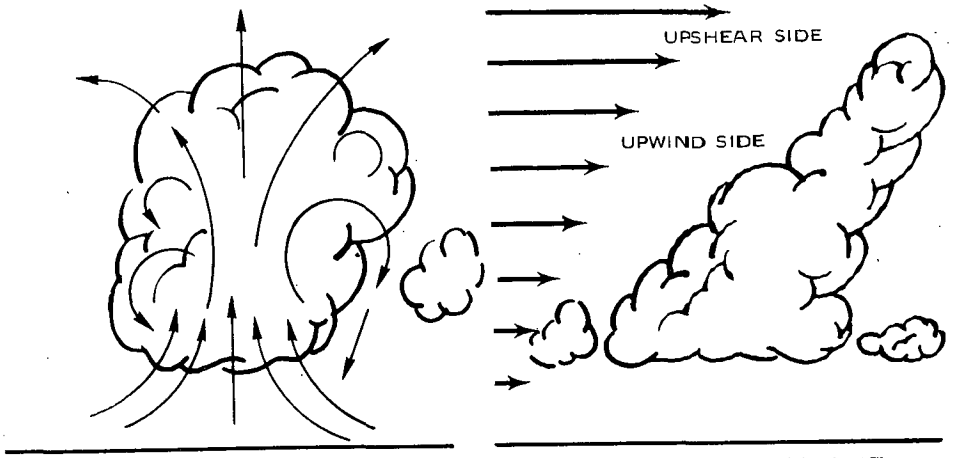
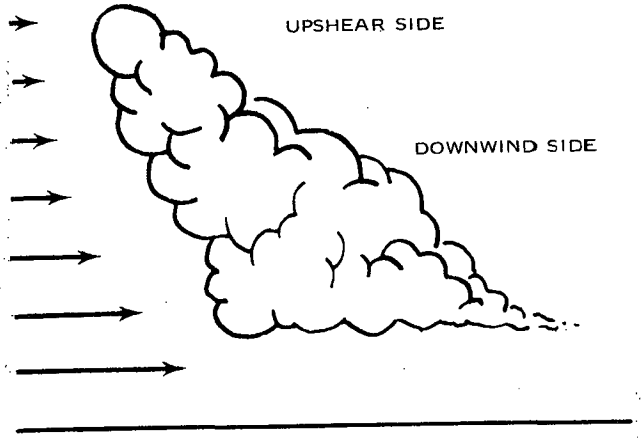


(a) Zero wind shear (Class A clouds).

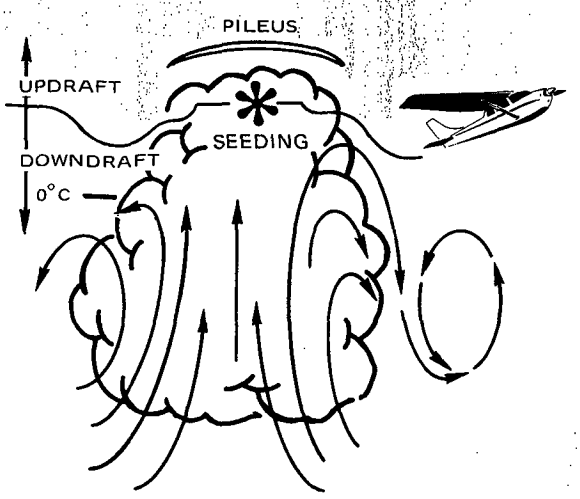
(b) Wind increases with altitude (Class B clouds).



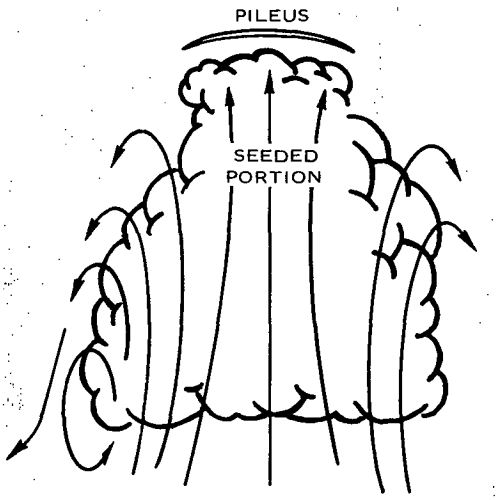
(c) Wind decreases with altitude (Class C clouds).

FIG. 1

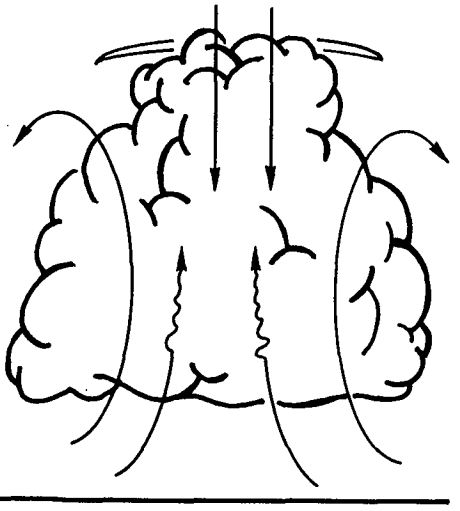
FIG. 1. Various Wind Shear Conditions.



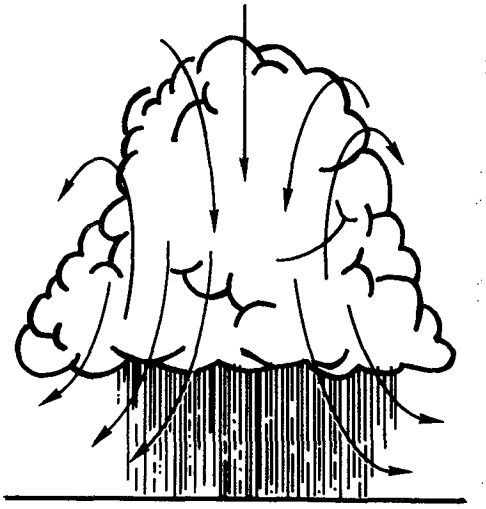
(a) Rapidly growing towers frequently develop a pileus directly above the updraft. This is a good indication of updraft position. Air comes in the bottom of the cloud, flows up through it, past the visible top and down around the sides, much like a bubble fountain. A downdraft surrounds the sides of the clouds, at least at seeding altitudes.



(b) Following seeding, the central portion rises rapidly and the base widens. Usually, the portion above the freezing level doubles in volume in three to five minutes. Updrafts inside are intensified, the total downdraft external to the cloud increases.



(c) At apex, the cloud ceases to grow vertically, the top begins to evaporate and begins a gentle descent into the mass beneath, where the droplets run into still ascending air carrying cloud water upward. The lower part turns dark and in.



(d) A rain shower develops as the cloud collapses. The sequence applies to single tower, seeded only once, with no attempt made to sustain growth, and closely resembles a typical rain shower process in the tropics, except that the presence of ice is not usual in natural tropical rain showers.

FIG. 2. Behavior of a Single Seeded Tower in the Absence of significant Wind Shear.

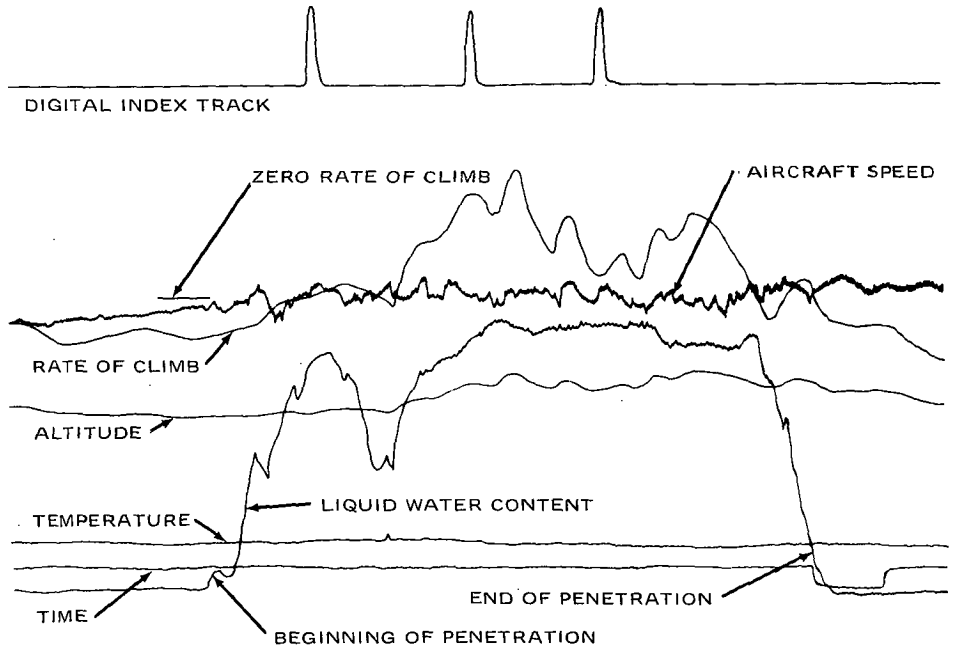


FIG. 3

FIG. 3. Partial Reproduction of a Minilab Strip Chart, Corresponding to a Seeding Penetration Over Baguio on 11 May 1969. Note the moderate downdrafts on either side of the cloud and the stronger updrafts inside the cloud. Note also the correlation of liquid water content with the two updrafts. This was an isolated cloud in a low shear wind regime.

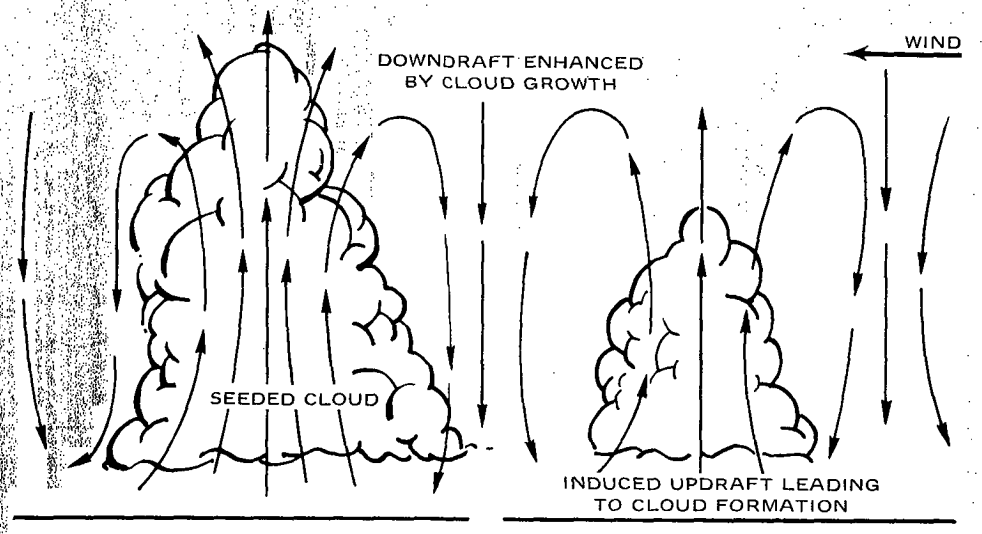
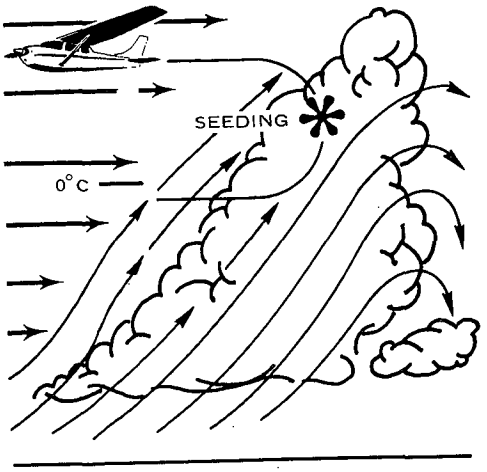
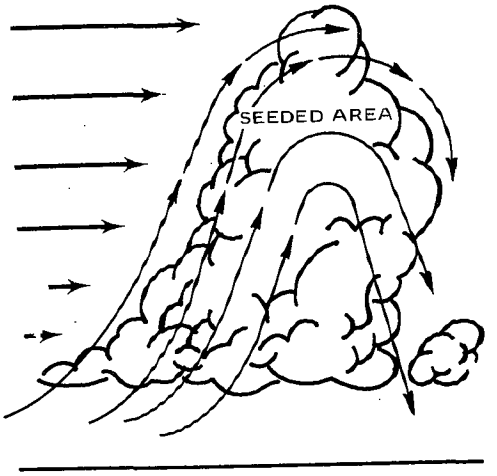


FIG. 4

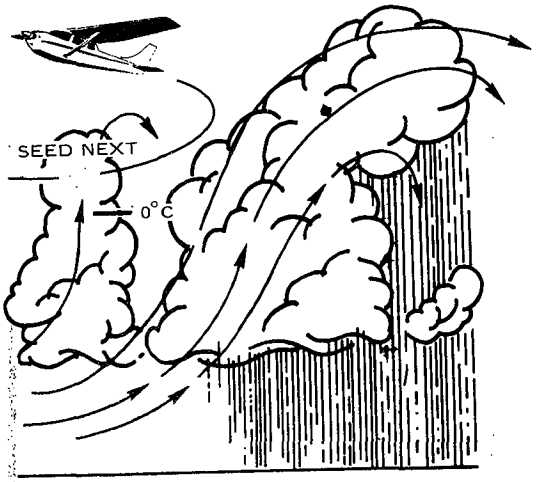
FIG. 4. Possible Mechanism for the Generation and Invigoration of Clouds Adjacent to Seeded Clouds. The enhanced updraft in the seeded cloud causes more air to flow down around the outside, producing a counter rotating cell at the side whereby an already existing updrafts at the side, is enhanced by induction of the corresponding downdraft. This results in more rapid uplift and increased condensation in the new cloud, hence, increased growth.



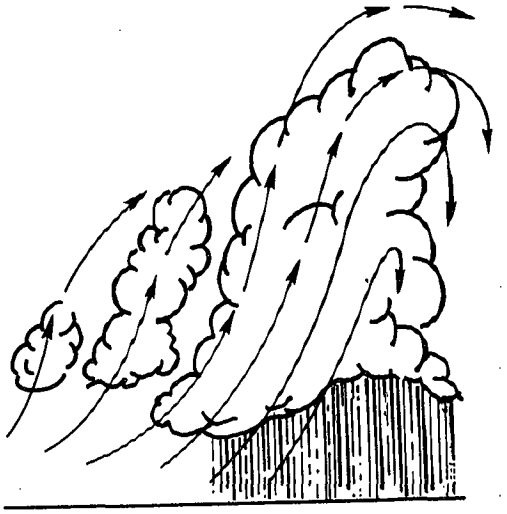
(a) Seeding is done in the upwind most turret that reaches to or above the level at which the nucleant can be expected to function, usually between the -2°C and -7°C levels. Penetration is from the side, across the shear; the charge is dropped in a recognizable updraft.



(b) The upshear edge steepens following seeding.



(c) A new tower develops in the entraining wave just upshear (upwind) of the area seeded; this is seeded next. It coalesces with the main mass following seeding and future seeding is done on newer growth.



(d) As the cloud develops, scud and new towers continue to form; the base of the main mass lowers to form a pedestal with an occasional low roll cloud just in front. Heaviest rain falls just aft the pedestal.

FIG. 5. Behavior of a Leaning Cloud in a Uniform, Gentle Wind Shear.

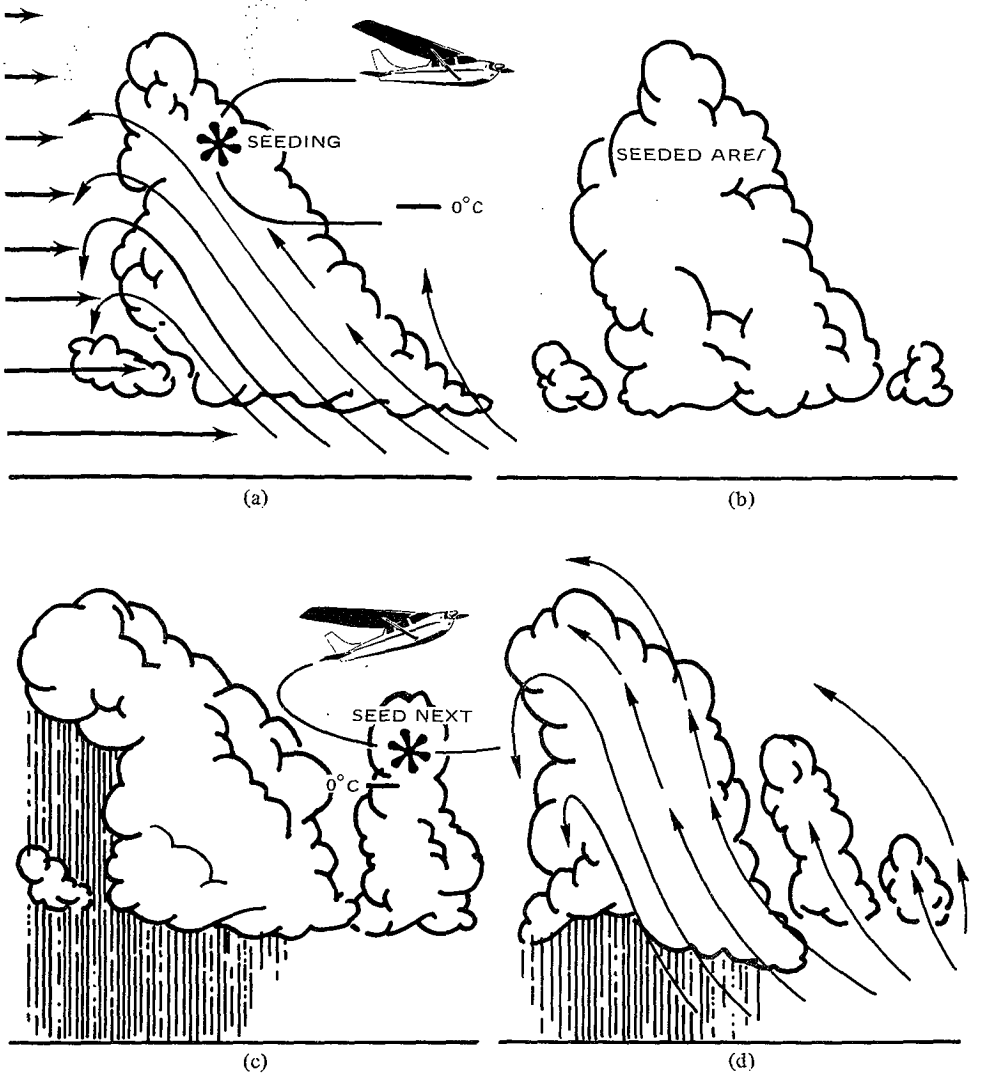


FIG. 6

FIG. 6. Behavior of Seeded Cloud in Reverse-Shear Wind Field

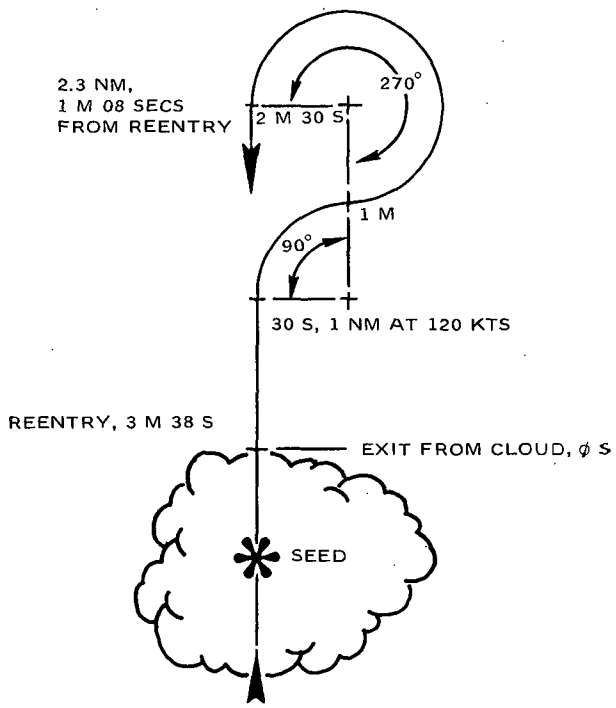


FIG. 7

FIG. 7. A 90 to 270 deg Reversal Turn for Purposes of Identifying the Part of a Cloud Just Traversed. The Aircraft is directed outbound on the original penetration heading for 30 seconds, then turned 90 deg to one side and then 270 deg to the other in standard rate turns (3 deg/sec). The whole procedure takes about 2 min 30 sec until one again accurately faces the cloud and permits another 1 min 8 sec of observation before repenetration. Distances are for an airspeed of 120 KTS. This procedure permits accurate identification of the seeded tower and exact repenetration if flown carefully.

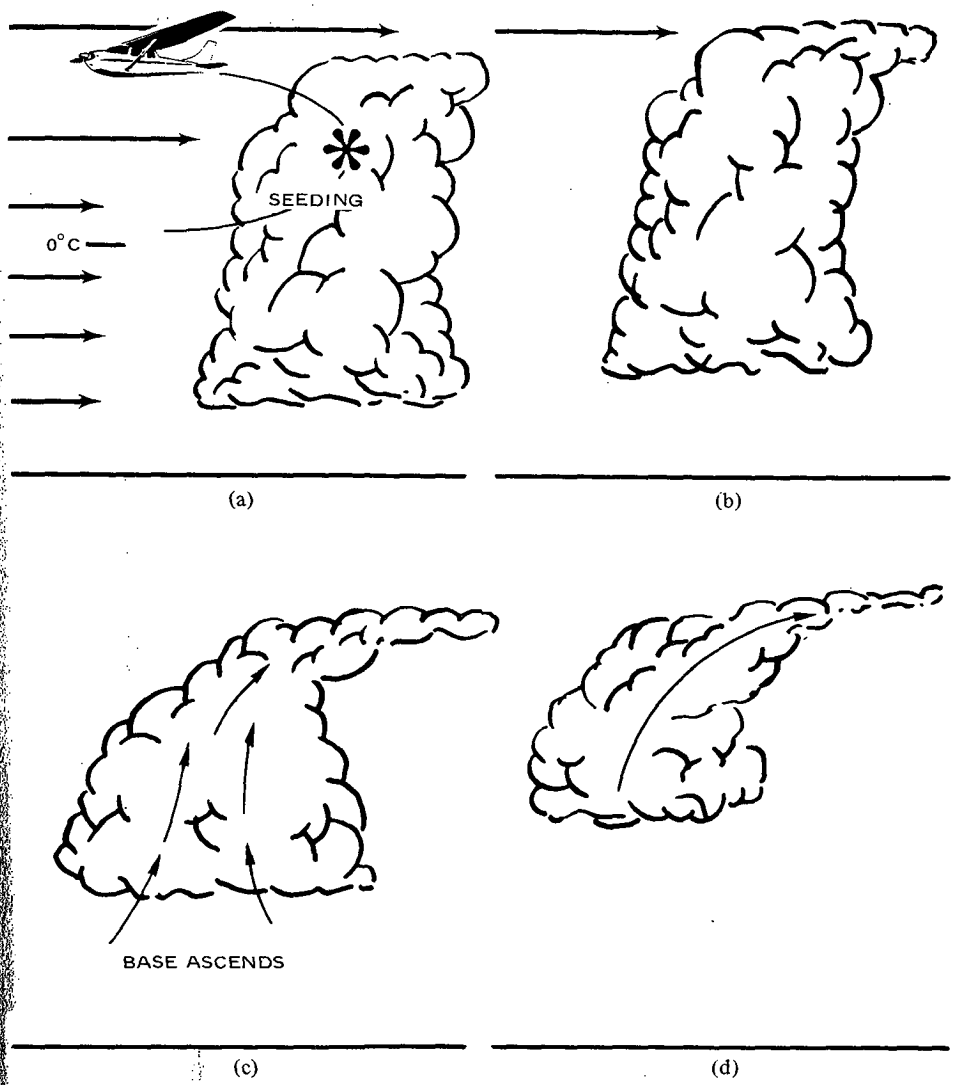


FIG. 8

FIG. 8. Effects of Seeding in Rapidly Varying Wind Field.

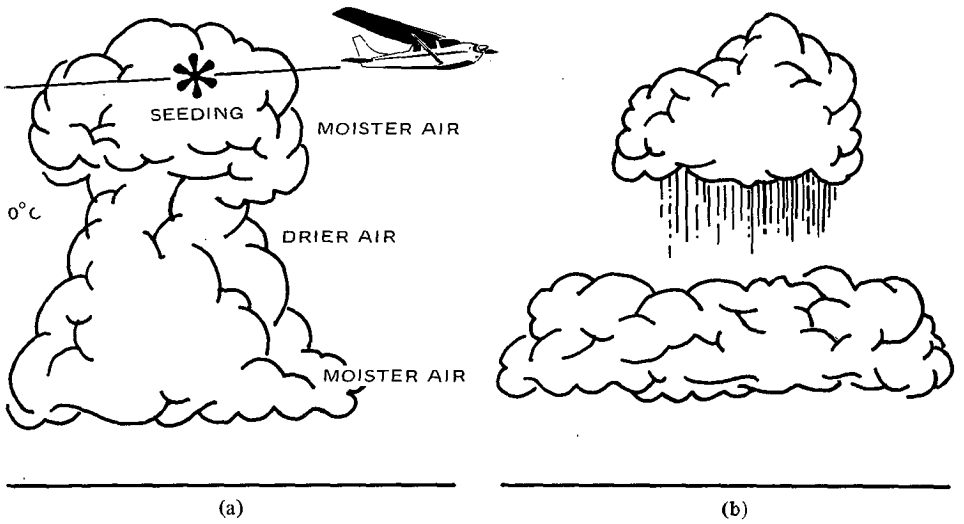


FIG. 9

FIG. 9. Weak Towers, or Towers Growing Through Dry Air Will Pull Apart in Midsection if Seeded too Vigorously.

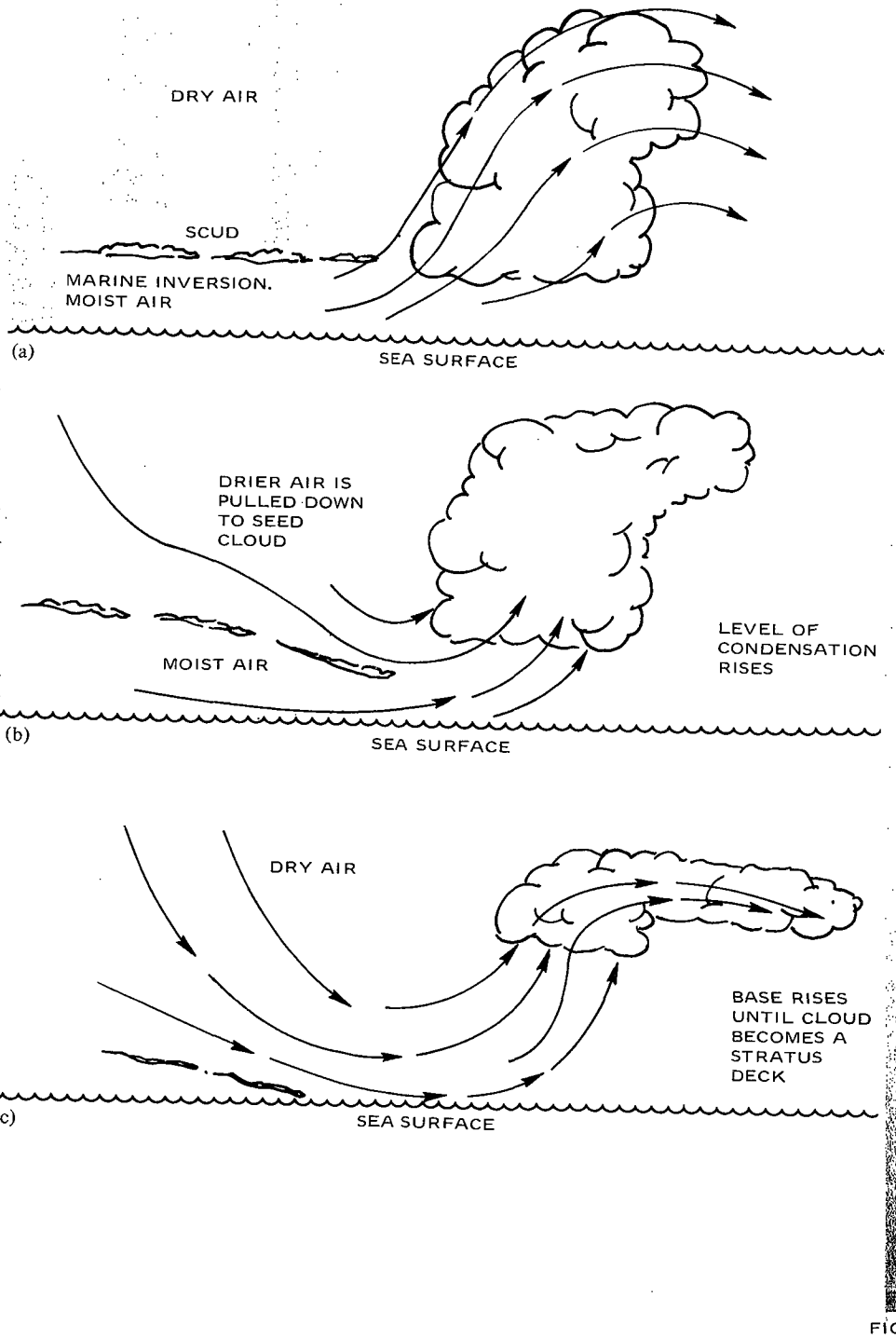


FIG. 10. Clouds Growing from Marine Inversion can be Self-limiting by Using More Air Than can be Furnished from Below an Inversion.

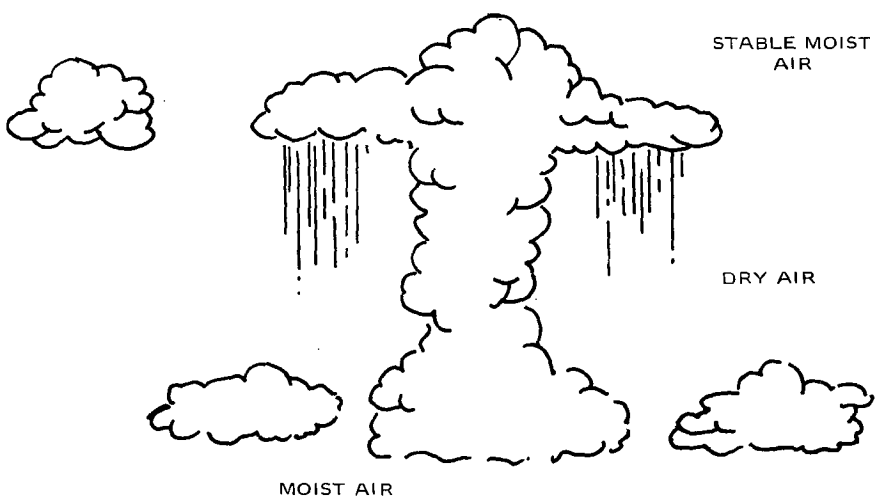


FIG. 11

FIG. 11. Sketch from Photo in GROMET II, St.-Amand, et al, 1971a, Showing Growth of Tower from Lower Inversion Through a Dry Layer into a Stable Moist Layer Aloft.

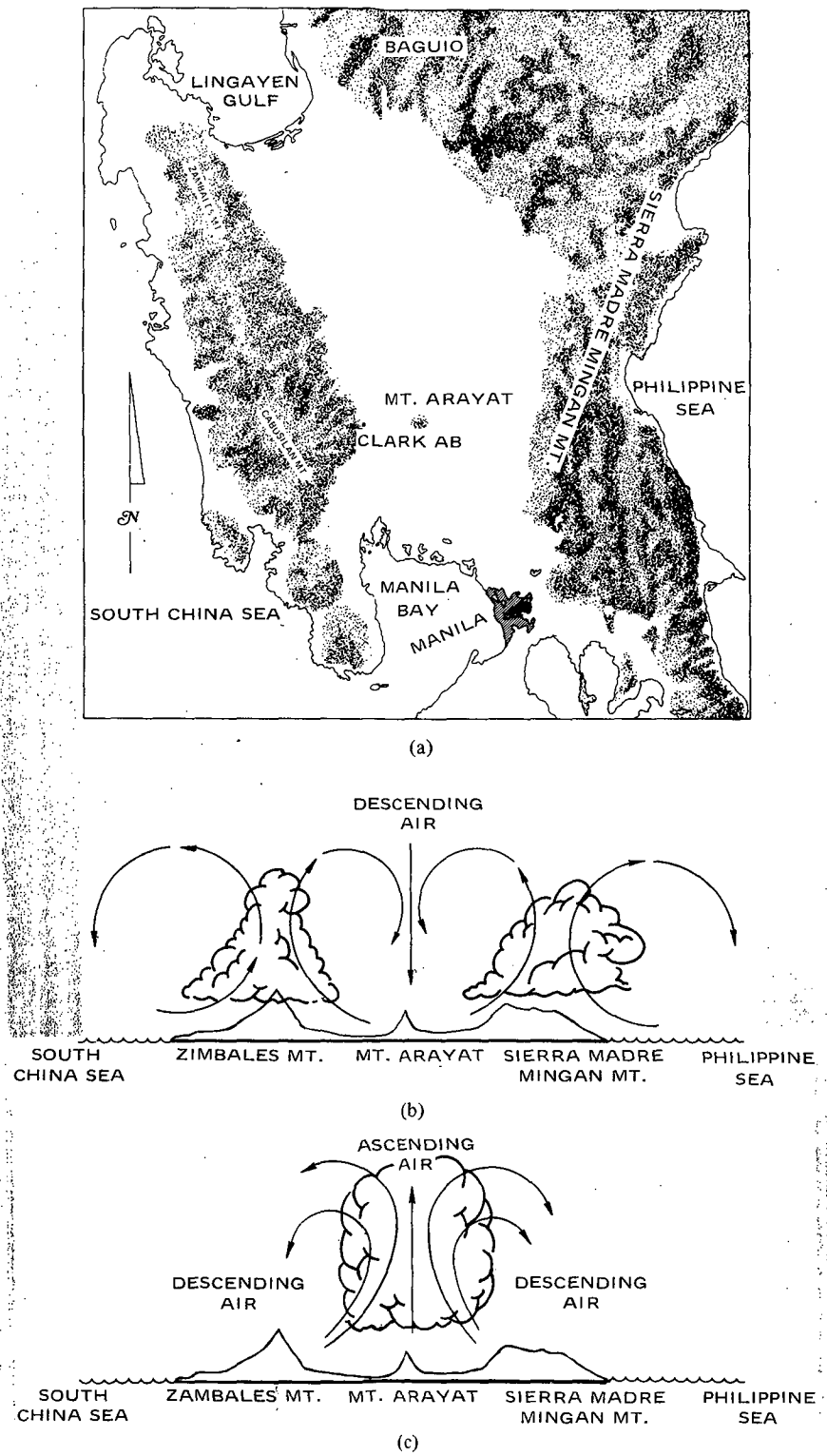


FIG. 12. (a) Croquis of Central Luzon; (b) Development of clouds over mountains suppresses cloud growth over Central Valley--air comes down and out Lingayen Gulf and Manila Bay; (c) Development of clouds over Central Valley can suppress clouds over Mountains if the valley is seeded first. Air comes in from Lingayen Gulf and Manila Bay starting sea breeze fronts.

DELAYED NUCLEATION EXPERIMENTS IN AN ISOTHERMAL CLOUD CHAMBER

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ABSTRACT

A two chamber isothermal cloud chamber was built to investigate the fate of AgI smoke particles. At concentrations as low as 0.3 mg/m^3, AgI particles remained in the air of the front chamber after ice fall-out and were able to subsequently initiate icing in the supercooled fog in the rear chamber. This is believed to shed some light on the so called "downwind effect" in seeding.

INTRODUCTION

Definable patterns of increased precipitation occurring some 50 to 100 miles downwind from the target area in which precipitation was initiated by seeding with AgI crystals have been observed (Weather Modification, 10th Annual Report, 1968). A contributing factor to an explanation of the phenomena may be related to a change with time in the effectiveness of the AgI seeds to act as a nucleant. It is postulated that even in situations where the number of supercooled water droplets exceeds the number of AgI nuclei introduced (this case), that: (1) not all these nuclei are used up in the time required to lower the total water content of the air to that required by the vapor pressure of ice at that temperature, and (2) the unused nuclei are still capable of initiating freezing if brought into the presence of a new supply of supercooled water droplets. It is possible that not all of the AgI nuclei that have been injected into a supercooled atmosphere or fog are effective immediately; some nuclei may not become effective until after a time delay, i.e., they may exhibit delayed nucleation. However, there is at present no physical evidence that two classes of AgI particles are formed during the combustion.

PROCEDURE

Experiments were conducted in an isothermal cloud chamber to check this thesis. A cloud chamber having a volume of 18.6 cubic meters was divided into two sections (8.65 and 9.96 cu meters) with a partition equipped with two doors. The doors could be sealed when closed to prevent leakage or diffusion of air between the two sections. A fog was produced in the front section by the condensation of steam. After the fog stabilized, this section was nucleated either (a) with AgI from the burning of a few milligrams of a pyrotechnic containing $AgIO_3$ or, (b) by the shock wave produced by discharging a CO_2 gas powered pistol. In either case, from 30 to 45 seconds were required for the appearance of the first ice crystals and about 4 to 5 minutes for the fog to dissipate completely. The back section was then fogged using steam and after it stabilized the door in the partition was opened. If the front section had been seeded with AgI crystals, nucleation occurred initially where the air masses from the two sections interdiffused; and then spread quickly throughout the rear section. However, when the front section was nucleated by the expansion of the CO_2 from the gas powered pistol, no nucleation occurred when the air masses from the two chambers interdiffused. The results are summarized in Table 1. This indicates that nucleation in the back section was by AgI crystals that did not participate in the initial nucleation.

TABLE 1

SUMMARY OF RESULTS

TEST NO.	TEMPERATURE OF FOG		NUCLEATION BY	NUCLEATION OBSERVED IN 2nd SECTION
	FRONT SECTION	BACK SECTION		
1	-6°C	-6°C	CO_2	No
2	-2°C	-2°C	85 mg pyro* 1.22 mg AgI/m^3	Yes
3	-2°C	-2°C	CO_2	No
4	-4.5°C	-4°C	CO_2	No
5	-7°C	-7°C	22 mg pyro 0.31 mg AgI/m^3	Yes
6	-7°C	-5°C	28 mg pyro 0.4 mg AgI/m^3	Yes, after 35 min. delay

*Pyrotechnic containing 15% $AgIO_3$, 12.45% AgI

The fogs produced in the two sections contained about 6 grams of water per cubic meter. A droplet size distribution count was made on one of the fogs using the McEwan, Drew Mirror Technique (1970). The mean fog droplet diameter was 1.32 microns with a standard deviation of 0.96 microns. This corresponds to a fog particle count in the order of 1.3×10^{12} particles per cubic meter. This average particle size is considerabley smaller than that reported by McEwan and Drew (1970) for a maritime fog and the values reported by Fletcher (1966) for clouds. This smaller size is attributed to the condensation process used to produce the fog since the fog was sampled very shortly after being produced, thereby allowing little time for droplet growth. Information is not available on the size of AgI particles produced by burning an $AgIO_3$-containing-pyrotechnic; however, Mason (1957) reports values of about 10^{13} nuclei at -10^{0}C for combustion of small coke nuts impregnated with an AgI solution. Using this value and assuming complete conversion of the $AgIO_3$ to AgI, this corresponds to an AgI particle concentration in the order of 4×10^{9} per cubic meter for the conditions of this experiment. This approximate calculation indicates that the number of fog droplets exceeded the number of AgI particles by a factor of about 1000. Thus, all of the AgI particles could have been consumed in the initial nucleation if they had been able to successfully collide with a water droplet in the 4 to 5 minutes required for the fog to disappear. The fact that the residual air mass still contained as effective ice inducing agent indicates that either not all of the AgI particles were initially effective or that they were not all consumed during the ice formation, and thus were available after a delay to nucleate the second air mass containing supercooled water droplets. On the other hand, where the ice formation was initiated by the CO_2 expansion, which of course produced no solid particles other than ice, nucleation of the second air mass did not occur, thus showing that second air masses' freezing was not due to submicroscopic ice embryos which did not settle out, or to the effects of residual ice crystals on the walls or floor of the chamber.

CONCLUSION

It is believed accretion of water vapor on ice embryos plays a major role in the removal of supercooled water droplets from a system. This process is fast enough that it is relatively easy for all the supercooled droplets in a fog to be used up before all the silver iodide particles from a smoke have successfully contacted a droplet to nucleate or to have condensed enough water vapor on its surface to grow to a size large enough to fall out. Thus, it may be that the "downwind" effect may be due to leftover nuclei being mixed in with more supercooled water vapor in an area of convergence, hence causing precipitation in an area remote from the original seeding site.

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THE USE OF HIGHLY CHARGED HYGROSCOPIC DROPS

FOR FOG DISPERSAL

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ABSTRACT

Hygroscopic solutions sprayed into a fog can be used to disperse the fog and to improve visibility. However, present techniques require such large amounts of material that cost and inconvenience make them unattractive for large scale routine use. This paper estimates the advantages to be gained from electrifying the drops of hygroscopic material.

The growth of an electrically neutral hygroscopic drop by diffusion of water vapor was calculated using Fukuta's equation. To this was added the growth by collision followed by coalescence with smaller uncharged droplets of the fog.

The growth by collision and coalescence for an electrically charged drop falling through a fog was calculated using Cochet's equations. Fukuta's equation was used to calculate the diffusional growth of a charged drop. The growth by diffusion was added to that by collision.

The uncharged drops of hygroscopic solution should grow from 40 to 88 microns in 200 meters of fall. Hygroscopic drops of 40 microns radius charged to the Rayleigh limit should grow to 112 microns, a gain of 22 times the initial volume.

These calculations were then used to estimate the fog clearing potential of electrically charged drops. It should be possible to increase the visibility in fog up to 20 times when treating advection type fogs with as little as 10 gallons per acre of agent. The visibility increase is less when a significant portion of the fog droplets is smaller than a few microns.

The feasibility of fog clearance can be improved if a method for charging the spray droplets to near the Rayleigh limit can be developed.

INTRODUCTION

A number of methods have been devised and used to clear fog. Fog occurring at temperatures below $0^{o}C$ and composed of liquid water droplets

can be cleared easily, if less than 1,000 meters thick, by seeding with nuclei that induce freezing. Water droplet fogs occurring in air warmer than $0^{o}C$ are much more difficult to eradicate. The techniques envisioned and tried include: heating the air to evaporate the fog, mixing dry air from above the fog with the fog to cause it to evaporate, filtering the fog from the air, sweeping the fog particles away by dropping various materials into it, drying the fog out by spraying or distributing hygroscopic agents in it, etc. These techniques and many variations of them have been successful under special conditions, but expense or operational difficulty has precluded wide spread use of any of them.

The Earth and Planetary Sciences Division, Michelson Laboratory at China Lake, California, has conducted extensive fog dispersal tests with various hygroscopic agents. Because of ease of handling, cheapness, hygroscopicity and innocuous or beneficial ecological effects, we have used a solution of urea, ammonium nitrate and water in approximately equimolar proportions. Sensu strictu this is not a solution but is a melt; the melting point of eutectic, urea-ammonium nitrate is depressed by the addition of water. The material and the results of the field trials and laboratory tests are reported in Blomerth, et al. (1970), Clark, et al, (1971), Wright, et al. (1972).

DROP SIZE CALCULATIONS

Diffusional Growth

Fukuta's equation (Fukuta 1970) was used to calculate the hygroscopic growth. For a solution drop in air of saturation ratio, S, the growth rate is

$$\frac{dm}{dt} = 4\pi r_s'(S-A)/\left[\frac{AMLL'}{RT_\infty^2 K f3_\alpha} + \frac{RT_\infty}{DMp_{\infty,sat} f3_\beta}\right], \qquad (1)$$

where

$$A = \frac{n}{n + in'} \exp\left[\frac{2\sigma' V_L'}{r_s' RT_\infty}\right] \qquad (2)$$

where

m = mass of drop
t = time
r_s' = radius of solution drop
S = saturation ratio
A = combination of Kelvin and solute effects, defined by Fukuta
M = molecular weight of water
L = latent heat of condensation of water vapor
L' = latent heat of condensation of water vapor in solution
R = universal gas constant
T_∞ = ambient temperature
K = thermal conductivity of air
$f_{3\alpha}$ = correction factor for temperature difference, defined by Fukuta
D = diffusion coefficient of water vapor in air
$p_{\infty}'sat$ = saturated water vapor pressure at ambient temperature, T_∞
$f_{3\beta}$ = correction factor for vapor density difference, defined by Fukuta
n = number of moles of solvent, that is, water
n' = number of moles of solute
i = van't Hoff factor for non-ideal solution
σ' = surface tension of solution drop
V_L' = molar volume of water in solution

This growth equation differs from previous equation (Maxwell, 1879; Rooth, 1957; and Langmuir, 1961) in that discrete vapor and temperature fields at the surface of growing drops are considered.

It is assumed, perhaps incorrectly, that an electrical charge will have no effect on the rate of growth of drops by diffusion of water vapor thereunto. The same equations are therefore used for water vapor accretion by both charged and uncharged drops.

Growth by Accretion, Uncharged Drops

The treatment here involves only vertical fall of the treatment drops through the fog. The uncharged drops are assumed to fall faster than the fog droplets and sweep them up by Smoluchowskian capture. No effects due to electrical charge or to diffusiophoresis are included.

The basic equation is

$$N = \pi \int_0^\infty \int_0^\infty (V_T - V_F)\,(r_s' + r)^2\, E n_T n_F dr_s' dr \qquad (3)$$

where

N = Number of collisions, equated to number of droplets collected per unit volume per second.
π = Ratio of circumference to diameter of a circle.
r = Radius of fog droplets.
V_T = Gravitational fall velocity of treatment drops.
V_F = Gravitational fall velocity of fog droplets.
E = Smolochowskian capture coefficient.
n_T = Number of treatment drops per unit volume.
n_F = Number of fog droplets per unit volume.

Assuming a monodispersed fog, in which the V_T is large compared to V_F, and a monodispersed treatment, this reduces to

$$N = \pi V_T (r_s' + r)^2 E n_T n_F \tag{4}$$

Because $E = f(V_T, V_F, r_s', r)$, calculation of capture must be done by a stepwise integration.

The volume accreted by the treatment and added to the treatment drops is

$$V_c = \frac{4}{3}\pi r^3 N \tag{5}$$

The resultant volume, V_R of the treatment drops after collection is

$$V_R = V_c + V_T \tag{6}$$

The coalescence factor in these calculations is assumed to be unity.

Growth by Accretion, Charged Drops

Because of electrical attraction a charged droplet can pull uncharged droplets to itself from a considerable distance. The capture coefficient should be therefore much larger than for gravitational sweep-out alone.

An equation developed by R. Cochet (1952) was used to calculate the coalescence growth of a charged solution drop of radius, r_s', capturing neutral fog droplets. The collection coefficient, ε, is for electrically charged droplets:

$$\varepsilon = \left(\frac{1}{r_s'}\right)^2 \left[\frac{45\lambda r^2 Q^2}{16\gamma g(r_s'^2 - r^2)}\right]^{2/5} \tag{7}$$

where

λ = the induction factor ≈ 1
Q = charge on the solution drop
γ = density of the solution drop
g = acceleration due to gravity

In this equation the inertia of the droplets and the hydrodynamic curvature of their trajectories are neglected. Thus, this equation holds only for highly charged drops. "As r_s' increases with growth, the charged drop formula becomes inaccurate and the inertia of the droplets and curvature of the streamlines near them has to be taken into account" Fuchs (1964). This error is present in the following calculations and the collection coefficient, as calculated, may be in error by as much as a factor of three at the low charge-to-mass ratios. The calculated collection coefficient may also be in error due to an effect on the collection coefficient of a drop falling in a spray of other like sized and charged drops. Because the effects of wake interaction are neglected, single drop calculations or even single drop experimental data probably only approximate the collection coefficients of a family of drops in a spray.

Details of Drop Growth Calculations

A digital computer program was coded to calculate the growth of treatment drops as they fell through fog. For an elapsed time, the mass gained (or lost) by the drop by water vapor diffusional growth (or evaporation) was added to the mass gained by accretion of fog droplets. The mass gained or lost by diffusion was calculated using Fukuta's equation. The mass gained by accretion was dependent on the Smolochowskian capture coefficient for an uncharged drop and on "ε" for a charged drop.

Since the effective cross-sectional area for an uncharged drop is derived from equation 4 as:

$$a_u = \pi E(r_s' + r)^2 \tag{8}$$

and the effective cross-sectional area swept out by the charged drop is computed by Cochet (1952) as

$$a_c = \pi \varepsilon r_s'^2 \tag{9}$$

the Smolochowskian capture coefficient, E, was corrected to E' where

$$E' = \left(\frac{r_s' + r}{r}\right)^2 E \tag{10}$$

so that E' and ε have the same physical significance. Values of the uncharged collision efficiencies reported by Davis, et al. (1970) and by Mason (1957) with 5μ radius droplets were approximated by

$$E' = 35\ r_s' \tag{11}$$

The error in this relation is small compared to diffusional growth and growth by accretion of charged drops between 10^{-3} and 10^{-2} centimeters.

The mass gained by a treatment drop in time t by accretion is

$$\int_0^t dm = \int_0^t (LWC)e\ \pi r_s'^2 V_o dt \tag{12}$$

where

(LWC) = the liquid water content which is the number of fog droplets per cm^3 times the mass of a fog droplet.

e = ε if the drop is charged, E' if uncharged.

$\pi r_s'^2$ = the cross-sectional area of the drop

V_o = difference in fall velocities of the drop and droplets

t = time

The difference in fall velocities of the drop and droplet is

$$V_o = V_s - \frac{2r^2\gamma g}{9\eta} \tag{13}$$

where

v_s = terminal velocity of the drop

$\frac{(2r^2\gamma g)}{9\eta}$ = terminal velocity of the fog droplets calculated by Stoke's equation

The terminal velocity of drops of radii larger than 10 microns cannot be accurately determined by Stoke's equation because the inertia term in the fluid mechanics equation can no longer be neglected. The results of many experimental investigations of the rate of settling of aerosol particles in air were summarized by Fuchs (1964, p.33). An empirical equation was used which fit these data for radii between 10 and 125μ.

$$V_s = 10^{5.5} r_s'^{1.8} \tag{14}$$

where V_s and r_s' are expressed in centimeters.

The maximum charge that a drop can be given without breaking is called the Rayleigh limit. At the Rayleigh limit

$$Q^2 = 16\pi\sigma' r_s'^3 \text{ (esu)} \qquad (15)$$

where σ' is the surface tension of the drop. Table 1 shows the maximum charge that can be carried by various sized drops.

TABLE 1

Charge Per Drop at Rayleigh Limit

Radius cm	Charge squared $(esu)^2$
10×10^{-4}	3.67×10^{-6}
20×10^{-4}	2.94×10^{-5}
40×10^{-4}	2.35×10^{-4}
100×10^{-4}	3.67×10^{-3}

The above equations were used to calculate the growth of a drop of given initial radius and charge. The initial charge was chosen to equal the Rayleigh limit in the charged drop calculations. For each time step the computer calculated the mass gained by diffusional growth and by accretion.

The computer added these masses to the initial mass, computed a new radius, calculated a new collection coefficient and other parameters which change in value as the drop grows, and then repeated the process until the drops were calculated to have fallen more than 200 meters. The growth was calculated by holding the relative humidity, liquid water content, and fog droplet radius constant for the entire 200 meters of fall. The fog droplets were considered to be monodisperse. The time integral was varied stepwise from 0.05 seconds to 60 seconds. The small time step was used initially because it was necessary to calculate precise values for the small drops; as the drop grew to a larger size and was diluted by the liquid and vapor water, larger integral times were possible.

Results of the Drop Growth Calculations

Figures 1-3 show the growth of 40-μ-radius drops of charged and uncharged hygroscopic agent and charged water falling in air with a relative humidity of 98% and containing 0.2 g/m^3 LWC of 5 μ droplets. Also shown in these Figures are the sweep area of the drops, the fall distance, mass of liquid water collected, and the mass of water vapor absorbed or evaporated.

VISIBILITY

Removing Fog Droplets

Sweep area, a, is the effective cross-sectional area under a falling drop.

$$a = \pi r_s'^2 e$$

The probability of sweep out can be calculated, assuming that the course of one droplet is not affected by the others.

If "a" is the effective cross section of each drop and A is the area of a horizontal plane upon which the drops impinge and X, the number of drops, is such that

$$Xa = A \tag{16}$$

The probability that a single drop will hit a specified point in A is

$$p = \frac{a}{A} = \frac{1}{X} \tag{17}$$

The probability, q, a single drop will not hit a specified point in A is

$$q = 1 - p = 1 - \frac{1}{X} \tag{18}$$

The probability that all X drops will not hit a specified point in A is therefore

$$q^X = (1 - \frac{1}{X})^X \tag{19}$$

For large values of X this is approximated by

$$q^X \cong e^{-1} \cong 0.3679 \tag{20}$$

The probability that a point will be hit by at least one of the X drops is therefore

$$1 - q^X = 1 - (1 - \frac{1}{X})^X \cong 1 - e^{-1} \cong 0.6321 \qquad (21)$$

If there are Y drops instead of X, the definition of p remains the same but the exponent becomes Y. The probability that a point will be hit by a drop becomes therefore

$$1 - (1 - \frac{1}{X})^Y \cong 1 - e^{-Y/X} \quad \text{(for large Y)} \qquad (22)$$

Hence by sweep out alone, one cannot be certain of removing all fog droplets with less than an infinite amount of material.

If the assumption is made that the calculations for a single drop are realistic for a monodisperse spray of multiple drops, then the fog clearing potential of the spray can be easily calculated.

The probability that a point will be hit by at least one drop is

$$P = 1 - e^{-Y/X} \qquad (23)$$

Calculations were performed where the number of drops was chosen such that X = Y, with X calculated using the minimum sweep for a single drop falling 200 meters through a fog of 5 μ droplet radius and 0.2 gram per cubic meter LWC. Table 2 shows these results for drops of 10, 40, and 100 μ initial radius. At these "standard dosages" 63% of the droplets would be swept out.

TABLE 2

Solution Drops Charged at the Rayleigh Limit Sufficient to Sweep Out 63% of the Fog

Initial Radius, μ	Minimum Sweep per drop, cm^2	Drops per cm^2	Gallons per acre	Grams per m^2
10	2.95×10^{-4}	3.4×10^{3}	0.153	0.195
40	9.0×10^{-4}	1.1×10^{3}	3.16	4.04
100	1.9×10^{-3}	5.3×10^{2}	24.0	30.4

Since $P = 1\text{-}e^{Y/X}$, three times the dosage shown in Table 1 would result in sweeping out 95% of the fog droplets.

Visibility Improvement

We have calculated the fall, growth and sweep area of one drop and the probability that a droplet will be hit by at least one drop. If we assume this drop can represent the average of all of the drops falling from a monodisperse spray treatment of a fog clearing operation, then we can calculate the improvement of visibility through the fog.

Four simplifications were made in order to ease the calculations of visibility improvement.

1. The liquid water content (LWC) was held constant at 0.2 g/m^3 for all drop growth calculations. Actually, in multiple treatments of a patch of 0.2 fog, the LWC would decrease after each treatment; thus the sweep area of each drop would not decrease as much (see Fig. 1-3).

2. The percentage of fog droplets larger than 5 microns in radius swept out by the treatment drops was the same as the percentage of 5 micron droplets swept out. Since ε is proportional to $[r^2/(r_s'^2 - r^2)]^{2/5}$ and sweep is proportional to ε, the percentage of the larger droplets swept out will actually be higher than 95%.

3. Almost all of the LWC of the fog is contained in those droplets larger than 5 microns in radius and the growth of the treatment drop will not be significantly affected by accretion with those fog droplets smaller than 5 microns. When this is not the case, this simplication would result in too large of a calculated sweep area.

4. Evaporation of fog droplets due to drying of the air by the hygroscopic agent was ignored.

For charged drops the sweep out is

$$a = \varepsilon \pi r_s'^2$$

since

$$\varepsilon \text{ is proportional to } \left(\frac{r^2}{r_s'^2 - r^2}\right)^{2/5}$$

$$a_i = a_5 \left[\frac{r_i^2 (r_s'^2 - 25)}{25 (r_s'^2 - r_i^2)}\right]^{2/5}$$

when

$$r_s' >> 5\mu$$

$$a_i = a_5 \left(\frac{r_i}{5}\right)^{4/5} \qquad (24)$$

where

a_5 = sweep on a 5 micron radius fog droplet

a_i = sweep on a fog droplet of radius r_i

The term "standard dose" will mean the quantity of treatment agent such that the sweep times the number of drops is equal to the target area, X = Y (see Table 2).

Now three standard doses will be sprayed onto a fog and the increase in visibility will be calculated.

Consider the probability of being swept out by three standard dosages as a function of fog droplet size. Since $P_i = 1 - e^{-Y/X_i}$ and $X_i = A/a_i$, then $P_i = 1 - \exp(-3a_i/a_5)$ when Y is chosen such that $Y = 3X_5$.

TABLE 3. The Probability of Being Swept Out

r_i (μ)	a_i/a_5	i
1	.276	.56
2	.480	.76
3	.665	.86
4	.837	.92
5	1.000	.95

Table 3 shows the values of P for droplet radii 5 micron and smaller. The number of droplets of any size which remain after a treatment with three standard dosages is $1-P_i$ (e.g., 0.14% of the 3 micron droplets remain).

The visibility in a fog can be calculated by an equation derived by Trabert (1901).

$$V = \frac{C\Sigma N_i r_i^3}{(LWC)\Sigma N_i r_i^2} \qquad (25)$$

where

V = the visibility in the fog
C = a numerical scattering factor, 2.6
N_i = the concentration of droplets of radius r_i.

For many fogs which have very few droplets smaller than 5 microns, the visibility would be 20 times greater after sweeping out 95% of all droplets 5 μ and larger. Another way of saying this is, V would be inversely proportional to the treated fog LWC.

For those fogs which have small droplet sizes we used the data of May (1961). In this careful study, the sampling of fog droplets was done with a cascade impactor (using gelatin coated slides); droplets of radii as small as 0.4 microns were measured, and corrections were made to the counts of droplets of radii smaller than 1 micron radius to compensate for the collection efficiency of the impactor slides. Although May did

not report the droplet size distribution, per se, he found that in 16 cases out of 28 the equation of Best (1951) fit his data. By use of a computer or a calculator the size distributions can be easily calculated. The Best equation is

$$1 - F = \exp\ [-(2r/a)^n] \qquad (26)$$

where

F = the fraction of the volume of water in the air comprised of droplets of radius less than r
a and n are constants

The size distributions of 6 of the 16 fogs (see Table 4) reported on were calculated. The 6 were chosen to cover the limits of a, n, LWC, and visibility. The number of droplets in each size range was reduced by 95% or less using Table 3 to compute the treated fog droplet concentration and distribution. Trabert's equation was then used to compute the visibility before and after treatment. Table 4 shows May's data and Table 5 the calculated values. The calculated increases in visibility varied from a factor of 3 to a factor of 20. The fogs with many small fog droplets of less than 0.6 microns showed the smallest improvements in visibility. These small droplets would rapidly evaporate if the treatment agent reduced the relative humidity, unless they had a large hygroscopic nuclei; in these cases even highly charged hygroscopic drops would be relatively ineffective. The majority of fogs, however, should have large visibility improvements after treatment. Table 5 shows the results of the calculations.

Table 6 shows the relative growth of a water drop charged at the Rayleigh limit falling through a fog of 5 μ radii droplets and 98% RH. The smaller drops have a higher efficiency but a longer fall time. At some point a longer fall time will negate the increase in efficiency (see Fig. 4).

TABLE 4. Data of May

Fog	Date	Visual Range (m)	Drop radius range (μ)	Number median radius (μ)	Volume median radius (μ)	Number of drops per cc	LWC g/m^3	n	a
1	19 Feb 1957	200	0.5-80	1.1	25	165	0.130	1.54	79.8
2	3 Apr 1957	300	0.6-160	1	43	54	0.046	1.53	112.7
3	6 Feb 1959	200	0.5-15	0.8	3.6	360	0.007	1.38	10
4	25 Jan 1960	160	1.3-21	10	12	23	0.13	5.58	26.5
5	17 Oct	160	0.5-32	1.4	18	39	0.117	3.40	39.7
6	13 Dec 1960	75	0.8-22	1.2	6.3	982	0.102	2.18	16.4

TABLE 5. Calculated Visibility Increase for Fogs Treated With Charged, Hygroscopic Drops

Fog	Visibility, meters		V_{tr}/V_{untr}
	treated	untreated	
1	5,770	700	8
2	24,800	2,700	9
3	6,240	2,000	3
4	9,200	460	20
5	12,900	690	19
6	1,800	270	7

TABLE 6. Water Drops Charged at the Rayleigh Limit Falling 200 Meters in a Fog of 5 μ droplets and 98% RH

Initial radius (μ)	Mass of fog collected per mass of agent (g/g)	Time of drop (sec)
12.5	234	1,200
25	51	600
40	18.4	400
50	11.3	330
100	2.5	163
200	.57	63

Discussion of Results of Visibility Calculations

The visibilities reported by May and those calculated by Trabert's equation were not in agreement. The reported visibilities were of lamp posts and were thus based on an arbitrary standard; the relative visibilities (ratio of reported to calculated) were in better agreement. Since the visibility improvement was a ratio of the calculated treated vs. calculated untreated, it should be a good measure of improvement.

Of the six fogs shown in Table 4, the particle size distribution of the 25 January 1960 fog is most typical of advection type fogs. Treating this type of fog increased the visibility by a factor of 20. The particle size distribution of the 6 February 1959 fog is somewhat typical of a haze (Green and Lane, 1964, p.4). Since the LWC of this fog was only 0.007 gram per cubic meter and the computer calculations of drop growth and sweep used 0.2 gram per cubic meter, the value of sweep used to calculate the visibility improvement was too small. For this fog (haze) the calculated improvement in visibility was 300%. Even this small improvement could be socially useful in smog abatement.

CONCLUSIONS

The use of urea-amonium nitrate-water, hygroscopic solution drops, electrically charged to the Rayleigh limit, will provide a method of fog dispersal wherein reasonable dosage rates would be sufficient to improve visibility by removing 95% of the fog droplets larger than 5 μ radius.

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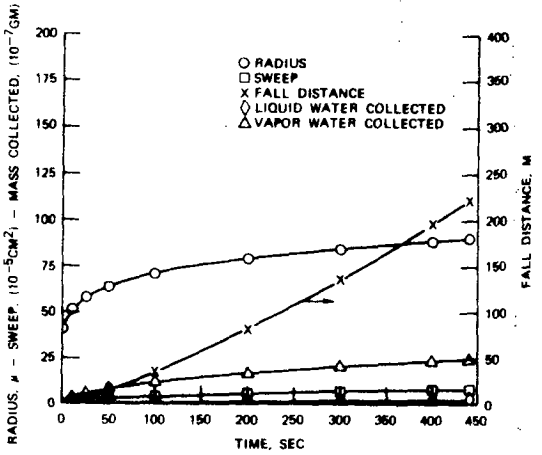

FIG 1. THE GROWTH OF AN UNCHARGED DROP OF UREA–AMMONIUM NITRATE SOLUTION FALLING IN A FOG OF 5μ RADIUS DROPLETS AND 98% RH.

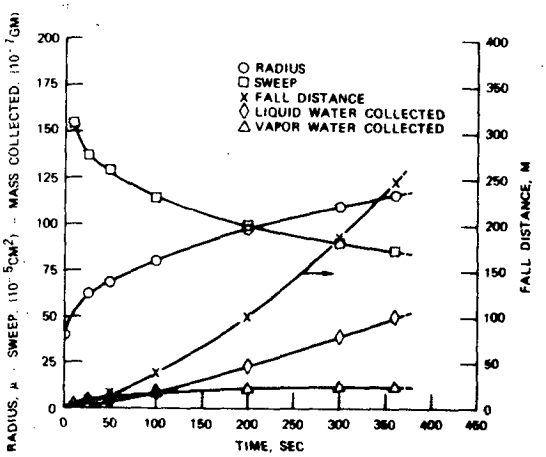

FIG 2. THE GROWTH OF A DROP OF UREA–AMMONIUM NITRATE SOLUTION CHARGED AT THE RAYLEIGH LIMIT FALLING IN A FOG OF 5μ RADIUS DROPLETS AND 98% RH.

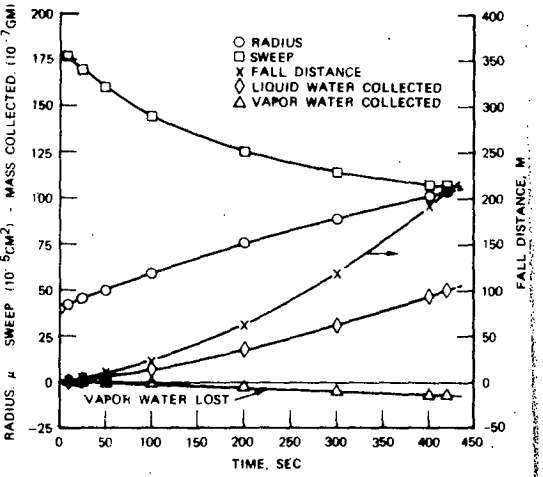

FIG 3. THE GROWTH OF A WATER DROP CHARGED AT THE RAYLEIGH LIMIT FALLING IN A FOG OF 5μ RADIUS DROPLETS AND 98% RH.

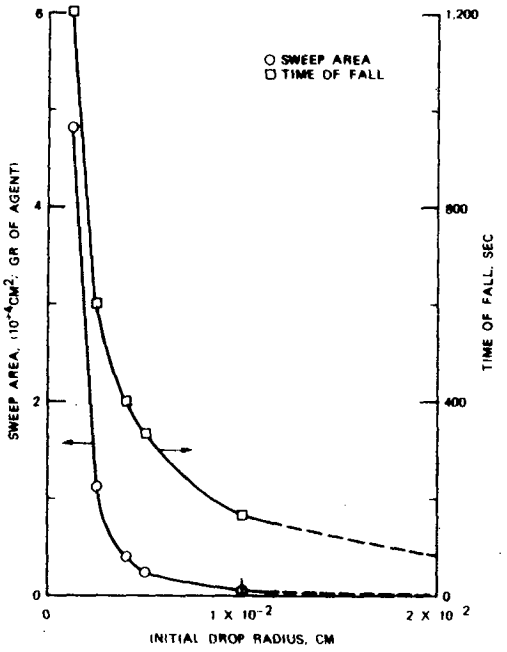

FIG 4. WATER DROPS CHARGED AT THE RAYLEIGH LIMIT FALLING 200 METERS IN A FOG OF 5μ RADIUS DROPLETS AND 98% RH.

FOG MODIFICATION BY MEANS OF ELECTRIFIED DROPLETS

by

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ABSTRACT

A system for induction charging of sprayed droplets was designed and built at the Naval Weapons Center. This system was tested in the field during actual fog conditions.

Theory of fog dispersal with charged droplets, system design, theoretical operation of the spray system, theoretical limitations, and practical operation of the spray system are discussed.

INTRODUCTION

Considerable evidence exists to suggest that electric forces may have a profound effect on the growth by collision and coalescence of droplets in warm clouds and fogs. Cochet (1951) showed theoretically that highly charged drops of less than about 60 microns radius would possess much larger collection efficiencies than similar but uncharged drops. Moore and Vonnegut (1960) observed the growth of precipitation in thunderclouds with very sensitive radar equipment. They estimated that for the precipitation to grow at the recorded rate the values of the droplet collection efficiencies must have been 4 to 10 times greater than the accepted values pertaining to non-electrified clouds. In order to explain the observed gushes of rain or hail which frequently follow lightning flashes in thunderstorms within short time intervals, Vonnegut and Moore (1960) put forward the theory that a lightning discharge introduces a large charge into the cloud opposite in polarity to the droplets in that region. These ions heavily charge the nearby droplets, and these droplets are forced outwards at very high velocities by forces of mutual repulsion. Coalescence with several other oppositely and lesser charged droplets would follow, leading to droplets large enough to precipitate out of the cloud and grow thereafter mainly by gravitational means.

*Dr. Smith was supported by U.S. Navy funds from July through Sept. 1971 during which time he was on an Excepted Appointment to the Naval Weapons Center, China Lake, California.

Clearly the influence of electric forces is a maximum for very small droplets, and the use of such small particles would result in the greatest economy of seeding material. However, the fall velocities of these very small droplets are very low, and larger droplets must be utilized in practical fog modification experiments to provide realistic fog dispersal times. The optimum droplet size is probably such that any reduction in the electrical effect due to droplet growth is offset by a compensating increase in the purely hydrodynamic collection efficiency. Droplets in the size range of 20 to 60 microns radius probably represent the optimum for the purposes of the fog modification procedures presently envisaged.

The successful introduction of large quantities of highly charged droplets into confined regions of a fog will result in the generation of substantial electric fields which may modify the interactions of natural fog droplets over regions of the fog beyond the immediate influence of the charged material. The general concensus of opinion seems to indicate that electric fields greater than 20 KV/metre will be required to significantly influence the stability of a natural fog, and while there will be considerable difficulties in engineering these large electric fields, the potential rewards are high enough to warrant further investigation.

This report covers the period from the July 7 to September 22, during which time a system for spraying suitable quantities of electrically charged droplets of both pure water and solution was designed and built. Preliminary testing of the completed system was also carried out during this period utilizing a manned hot-air balloon as a stable support platform for the spray rig.

DESIGN OF THE SPRAY SYSTEM

Many different methods of producing highly charged droplets were investigated, all of which relied upon the same basic principle. In all cases, the electrical charging system was arranged in such a manner that droplets were produced in the region of an intense electric field and thus acquired their charges by induction.

Initially, attempts were made to produce charged droplets by allowing water to flow over one electrode of a parallel plate capacitor across which a potential of several kilovolts was applied. This system produced drops which were made larger than those required, and when steps were taken to reduce the size of the drops produced these smaller drops were attracted back to the high voltage electrode.

A technique described by Vonnegut and Neubauer (1952) for producing monodisperse highly charged droplets of pure water or salt solutions was also investigated. The equipment consists basically of a fine glass capillary connected to a reservoir of the liquid in question arranged so that there is a very slow flow rate of liquid from the tip of the

capillary. A wire connected to a high voltage supply is inserted in the liquid. Above a critical voltage, determined empirically for a given experimental system (typically around 10 KV), a fine stream of droplets all carrying charges approaching the limiting charge is ejected from the capillary tip. Unfortunately, the theory governing the mode of operation of this superficially simple system is largely undefined, although it appears that some degree of control may be exercised by variations in the bore of the capillary tube, the liquid flow rate under conditions of zero potential (governed by the head of liquid), and the type and strength of the liquid of solution utilized. It has proved possible to produce steady streams of almost monodisperse droplets with radii between 20 and 50 microns at rates of a few hundred per second. However, there is no obvious way to adapt this system so that it may produce the vast numbers of droplets required in a practical cloud seeding experiment. Furthermore, in a practical system, space charge would build up around the capillary tips reducing the intense electric field in this region, thus modifying continually the operating conditions. Although this difficulty could be surmounted using induction rings and must lower electric potentials, the droplets produced in this manner are attracted to the induction rings. Therefore, a practical system would require auxiliary air blowers.

Visits were made to two commerical companies specializing in electrostatic paint spraying to observe their equipment in operation.

One system made by De Vilbin utilized an ordinary compressed air-driven paint gun which was fitted with an electrode operating at 30 KV. This system charged the issuing stream of droplets both by induction and by some ionic capture, with the ions being generated from the sharpened end of the high voltage electrode. Spray rates approaching one gal/min could be attained using a single gun, although the electric current carried on the droplets did not increase linearly with the spray rate. It was estimated that the droplets produced had approximately a 100-micron radius, and that the maximum current carried by the droplets was in the region of 20 μA. The principal disadvantage of the system was that large quantities of compressed air were required, but the technique would certainly warrant further investigation.

The second commerical process investigated was that operated by Ransburg Electro-Coating Corporation which utilized a spinning disk rotating at about 1,000 rpm. The spray liquid is fed into a well at the centre of the disk, is centrifugally accelerated across the surface, and is ejected from the sharpened edge of the disk in the form of fine droplets. The disk is maintained at a potential of 100 KV relative to the surrounding grounded screen (and objects to be painted), and thus the particles become electrically charged as they leave the disk. The principal difficulties are that some means of preventing the droplets from reaching the grounded screen must be found; in addition, the liquid flow rates for commerically available disks are rather low. This technique does, however, show tremendous promise as the droplets produced tend to possess a very narrow size distribution.

One promising spray nozzle was developed by Radon Loveland and consisted of a narrow slit through which water was forced at high pressure. The droplets were charged by applying a potential between the spray nozzle and a plate with a larger slit in it through which the stream of droplets passed. Air was blown through the system in order to help break up the jet of water and to carry the droplets away from the charging system. This technique gave droplet spray currents of approximately 16 μA with charging potentials of 5 KV and flow rates of approximately 1/2 gal/min. This charging rate corresponds to charges on the droplets of around 1/50 of the Rayleigh limit charge. Unfortunately, the compressed air requirement of this nozzle was too high for the present application, and, although further work was carried out on the nozzle, the difficulties could not be overcome in the time available.

The technique finally adopted for use in the present experiments makes use of single fluid spray nozzles which provide a 30° hollow cone spray pattern with flow rates of 8 gal/hr at fluid pressures of 125 psi. These nozzles were chosen because they gave the optimum available droplet size distribution (Fig. 1) and were fitted with simple cylindrical electrodes concentric with the spray cone and mounted to the body of the nozzle with machined Teflon insulators. This system gave droplet spray currents of 5 μA for a single nozzle when operated with a potential of 3 KV on the carefully adjusted cylindrical electrode. This charging current corresponds to a charge of approximately 1/30 of the Rayleigh limit charge on the droplets, assuming that the charge is shared as a fixed fraction of the limiting charge.

For the practical field trials, an octagonal array with two orthogonal cross-members was built out of 2-foot sections of 5/8-inch diameter pipe. Between each of the 2-foot sections, T-pieces were fitted to allow up to 60 spray nozzles to be fitted to the rig; T-pieces not fitted with nozzles were sealed with blanking plugs. The spray rig was operated in the field with 50 nozzles fitted which gave a total liquid spray rate of 6 gal/min at a pressure of 100 psi. A 25-gallon tank of liquid mounted in the balloon gondola was used to feed the sprayer system through 30 feet of flexible pressure hose, and the tank was pressurized from a small high pressure gas bottle. The electrical potential for the induction rings was provided from a stack of 90-volt radio batteries, and the charging rings were connected to this high voltage pack through separate 1-megohm 1/2-watt resistors, thus preventing a short circuit in one spray nozzle from closing down the whole system.

THEORETICAL OPERATION OF THE SPRAY SYSTEM

Prior to the commencement of the field trials of the spray system, some concern was expressed about the effect of the very small droplets produced by the spray nozzles. Although these tiny particles (<10 microns

radius) comprise a very small fraction of the total mass of sprayed liquid, they account for a very large fraction of the total number of particles produced. When introduced into the fog, these droplets would grow very rapidly initially, but would cease growing while still too small to fall rapidly out of the fog. Thus these particles would have a stabilizing influence upon the fog which would completely mask any desirable effects from the useful larger droplets. It seems possible, however, that the high fields which may be produced by the spraying of the charged droplets could act upon these harmful small particles to force them back to the grounded spray rig. A simple computer model, described below, was therefore used to estimate the magnitude of these electric fields and to calculate their influence on these small droplets.

A MODEL OF THE MOVEMENT OF CHARGED DROPLETS UNDER THE INFLUENCE OF THEIR CHARGES.

The Model

A very simple model, shown in Figure 2, has been adopted where the droplets are sprayed from the rig vertically downwards and are allowed to come to rest after they have lost their initial momentum. If we assume that Stoke's law is valid, the stop distance, L, of a particle of radius, r, is given by the equation

$$L = \frac{2Vr^2\gamma}{9\eta}$$

where V is the initial droplet velocity, η is the viscosity of air, and γ is the droplet density. Since the larger particles possess greater kinetic energy than the smaller particles, they will travel a greater distance, and the droplets will thus be arrayed in layers, the position of these layers depending upon particle size. Each layer of charged droplets gives an electric field at a point P both directly and an image charge in the spray rig above, which is assumed to be a conducting plane. The electric field at point P produced by layer AB is given by the equation

$$E = \frac{qN}{2\pi toR^2}\left(1 - \frac{a}{(a^2 + R^2)^{1/2}}\right) + \left(1 - \frac{a + b}{((a + b)^2 + R^2)^{1/2}}\right)$$

where q and N are the charge per particle and number of particles in layer AB, respectively, R is the radius of the layer, and a and b are the distances between the layer AB and point P and the rig, respectively.

The contribution of each layer may be summed to give the total electric field at the point P. By repeating this process, the electric field at all points along the axis XY may be calculated. This electric field gives a force on each charged particle which may oppose or enhance

the gravitational force. By taking the net force on each size of particle, the velocity and direction of travel of a particle in each layer was calculated, assuming that the droplets obeyed Stoke's law.

In the majority of cases, the charge was assumed to be distributed over the droplets so they all possessed a given fraction of the Rayleigh limit charge (i.e.:$q \propto r^{1.5}$). However, when the charge was distributed evenly over the surfaces of the particles (i.e.: $q \propto r^{2.0}$), there was only a slight difference in the calculated electric fields.

Limitations of the Model

The principal limitation of the model is that it presents only a static picture of the charge distribution and does not allow the droplets to move under the influence of gravity or the electric field present. However, the ejection velocity of the particles from the sprays was much greater than the natural fall velocities, and the computations were carried out for the spraying of different quantities of liquid in order to give an estimate of the initial build-up of the electric field.

The droplets do not generally obey Stoke's law when they are subject to the very intense forces exerted upon them by the high electric fields generated; however, towards the region where the direction of motion of the droplets is reversed, the approximation becomes increasingly accurate.

Also, since very large numbers of droplets are sprayed, the particles tend to travel as a cloud by entraining the surrounding air. To compensate for this effect, the stop distance was arbitrarily increased by a factor of 10 in order to give some estimate of the influence of the stop distance upon the resultant electric field.

A further limitation is that the electric fields and droplet velocities were only calculated along the axis of the system; at the extremities of the distribution, the direction and magnitude of both the electric fields and particle motions would be somewhat different.

Results and Conclusions

The results of the computations utilizing the model are presented graphically as Figures 3 to 9. The spraying rate at which the rig was operated was approximately 6 gal/min, thus the spraying times for 5 gallons, 1/10 gallon, and 1/200 gallon are 50 seconds, 1 second, and 1/20 second respectively. The main features of the graphs are the reversal positions of the electric field and the droplet velocities. In this region, the electric force and gravitational force on the particles almost cancel out leaving a very low remaining force. It may also be noted that the electric fields produced are quite large even in the case of the spraying of relatively small amounts of material. Even though the

stop distance criterion for the separation of the droplets according to size may not operate in practice, due to the tendency of the particles to travel as a cloud, we may still expect quite high electric fields to be created which would most certainly oppose the introduction of further charged droplets. This opposition would be most effective in the case of the very small particles. The cut-off achieved in practice could only be calculated by a greatly improved model which is considered to be beyond the scope of this investigation.

PRACTICAL OPERATION OF THE SPRAY SYSTEM

In order to test the operation of the spray rig, it was mounted upon sawhorses approximately 1 metre from the ground. With this arrangement, the total current flowing from the rig was measured by inserting a meter in the ground return line and electric currents of approximately 300 μA were reliably obtained. The spray rig was then tested while suspended from the balloon. It was found that with the rig at a similar height from the ground the current in the ground return line was only 30 to 40 μA. Furthermore, as the rig was raised to an altitude of about 10 metres, this current fell to approximately 4 μA. It was immediately apparent that the spraying of the charged droplets was in some way self-limiting, particularly when the spray rig was operated on the hot air balloon. Several possible explanations for the observed phenomena will be discussed in the following sections of this report.

The variation of the ground current with altitude must be due to the influence of the ground surface upon the charged particle distribution. Clearly charged droplets are removed from the system when they hit the ground, thereby reducing the electric field at the spray rig. Also, when the spray is close to the ground, the charged particles will "see" an image charge in the ground plane thus reducing still further the electric field in the region between spray rig and ground.

When the spray rig is situated away from the ground, the ground surface will have less influence upon the system and also more charge will build up around the spray rig. The resultant higher electric fields will force more material back to the rig. It is difficult to explain such a dramatic current reduction from about 30 μA to 4 μA on the basis of the removal of charged droplets, since this would require the removal of about 60 percent of the fluid; photographs show this clearly to not be the case. The only way in which this process would be possible would be if a very small fraction of the sprayed droplets carried the majority of the charge with the majority of the droplets remaining essentially electrically neutral. This hypothesis could be checked quite readily by measuring the charges upon the individual spray droplets. It would be difficult to explain the reduced current on the basis of the opposition of the induction field by the electric field due to the space charge as the local field within the electrode region is approximately 300 KV/metre.

The burners on the hot-air balloon must represent a powerful ion generator and it is therefore possible that these burners act as a potential equalizer thus counterbalancing the electric current to ground. This process also has the advantage that it could account for the ten-fold difference in current observed between the balloon-borne system and the system mounted upon the sawhorses.

When the electric field at the spray rig builds up to values approximating those calculated for Figures 3 to 9, corona discharges will occur at the rig, thus releasing ions opposite in sign to the charge upon the spray droplets. These ions will combine with the droplets, neutralizing their charges and reducing the ground current to the spray rig. It is difficult to estimate the magnitude of electric field sufficient to cause this ionic discharge to take place, but field greater than 5 or 10 KV/metre should give rise to considerable corona currents. To reduce these corona currents, steps must be taken to ensure that the spray rig has all sharp edges and sharply pointed fittings modified or removed. Ultimately, the spray rig may have to be completely redesigned in order to give as smooth a surface as is practically possible. In the current tests, electric fields as high as 3 to 4 KV/metre were measured at the ground utilizing a polonium probe field meter. With electric fields only a little stronger than these values, appreciable ionic discharge might be expected to take place at the ground, thus limiting the release of charged particles, at least in clear air. In a foggy environment, ionic charges released from the ground would be captured very quickly by fog droplets near the ground, thus trapping the charge on particles with much lower mobility than the ions. The electric field within the fog could then be built up to much higher values, and these strong electric fields would modify the interactions of natural fog droplets in the volume between the two regions of oppositely charged droplets.

COMMENTS AND RECOMMENDATIONS

One of the major improvements which could be made with most fog modification projects would be the use of droplets which are as nearly monodisperse as possible. At present, the atomization of large quantities of liquid requires the use of spray nozzles which tend to give droplet size spectra which are much too wide for the optimum fog modification effect. I would therefore recommend that a tremendous effort be expended in trying to improve the existing spray equipment and that novel atomization techniques be further investigated. An investigation into the use of spinning disk systems might be particularly profitable. If electrically charged droplets were required, it may be possible to produce these particles with ordinary single fluid spray nozzles and then to pass them through a corona charging device similar to those used in electrostatic precipitation (see White, 1951). The dimensions and electrical fields used for such a device could probably be arranged so the smaller, undesirable droplets were precipitated out electrostatically.

A future spray system for producing electrically charged droplets must also be very carefully designed to minimize the occurrence of corona discharge which tends to neutralize the spray droplets. Spray rigs with an external spheroidal outline in which all external projections were removed so that high electric fields between the sprayed cloud and the earthed rig could be maintained without breakdown might be contemplated. It might also be possible to conduct electrical experiments utilizing an insulating tube such as that built by Food Machinery Corporation to blow charged droplets into the inner regions of the fog.

Detailed studies must be made of the effect of the introduction of charged droplets into a fog. Initially, this work could consist of a theoretical fog model. The model must be capable of simulating droplet interactions, calculating electrical fields within the fog, showing the influence of the ground concerning image charges and corona discharge currents, and calculating the effects of any electrically induced droplet motions upon the hydrodynamic stability of the fog. A further refinement might be the inclusion of the capability of droplet growth by condensation. This model would be used to predict the effect of the introduction of charged particles into a real fog and should be capable of giving reliable estimates of the amount of material and charges required to modify natural fogs successfully.

Experiments could also be performed in the laboratory to make measurements of the growth of charged droplets and the influence of electric fields upon fog dissipation.

Many of the problems associated with the introduction of charged particles into the atmosphere and the influence of these charged particles upon cloud and fog stability have been considered by workers in the field of cloud physics, particularly Vonnegut, Moore and Colgate. A list of relevant publications is included at the end of this report.

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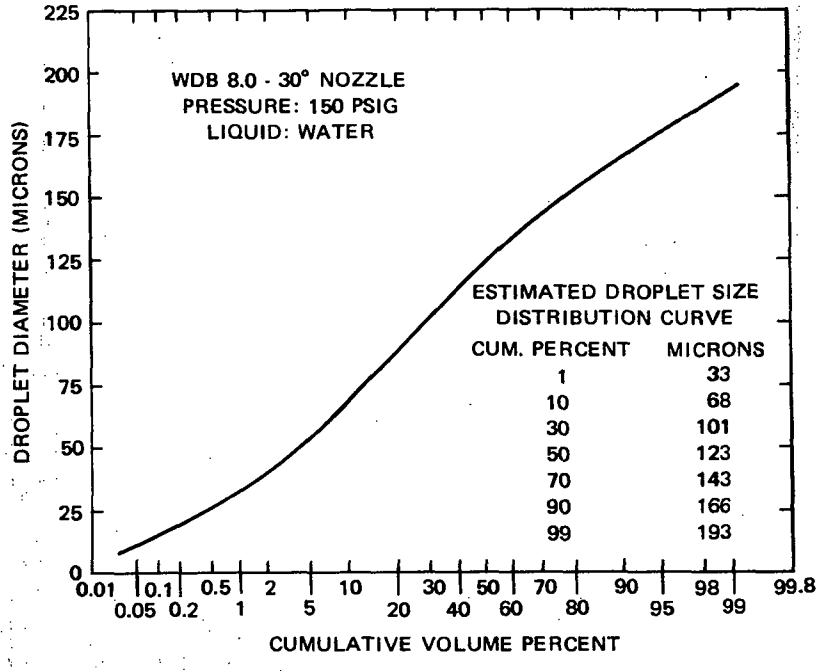

FIGURE 1

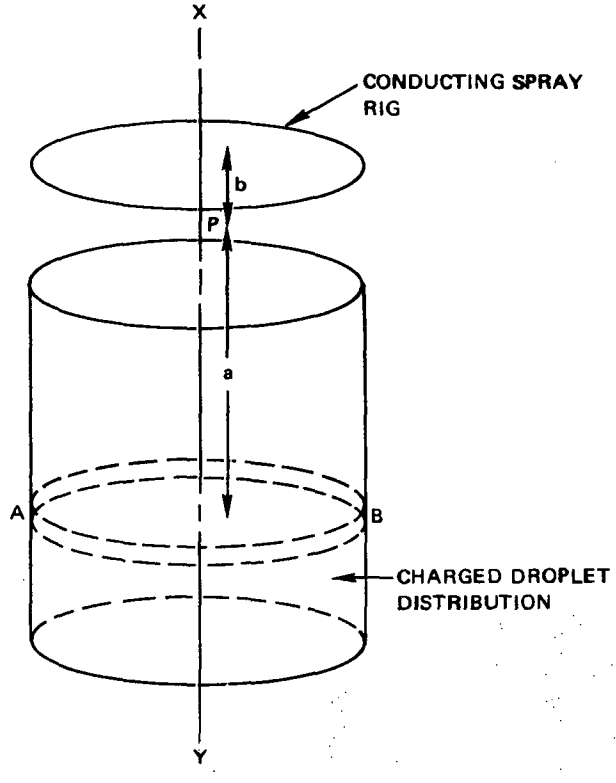

FIGURE 2

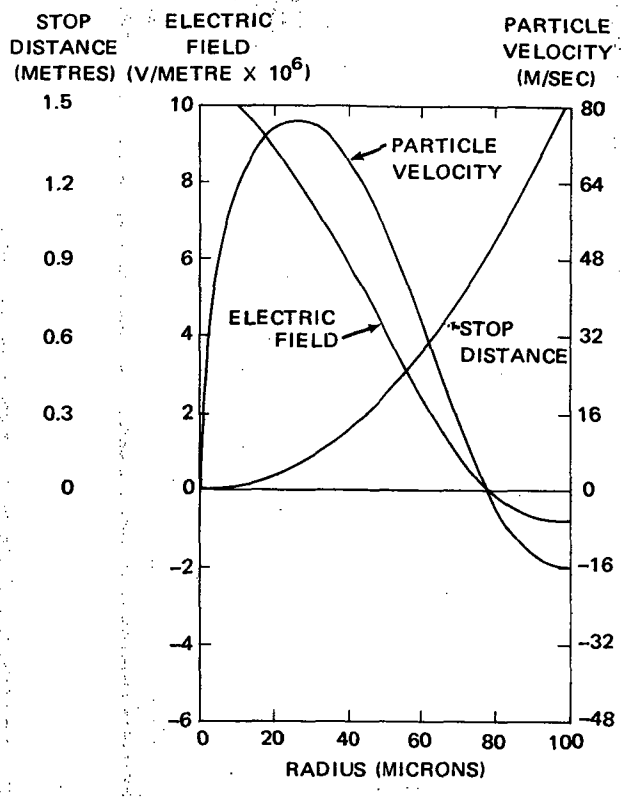

FIGURE 3

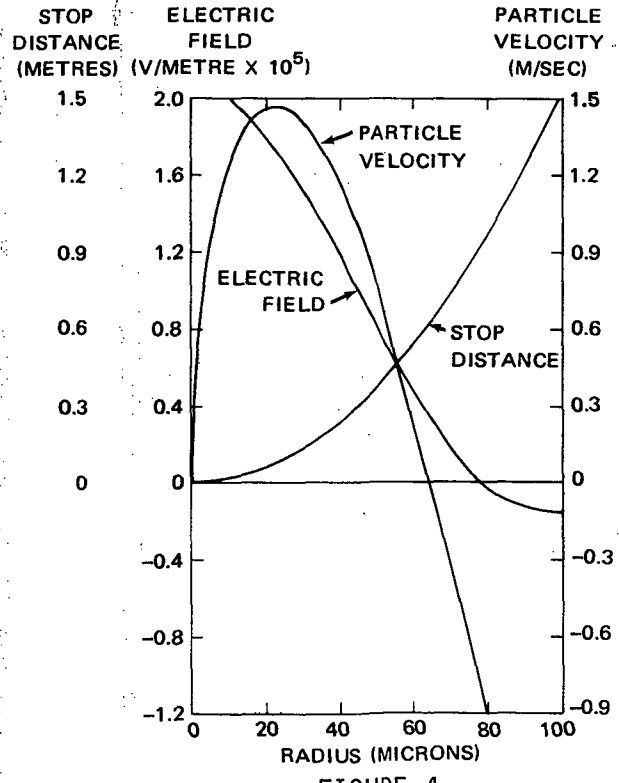

FIGURE 4

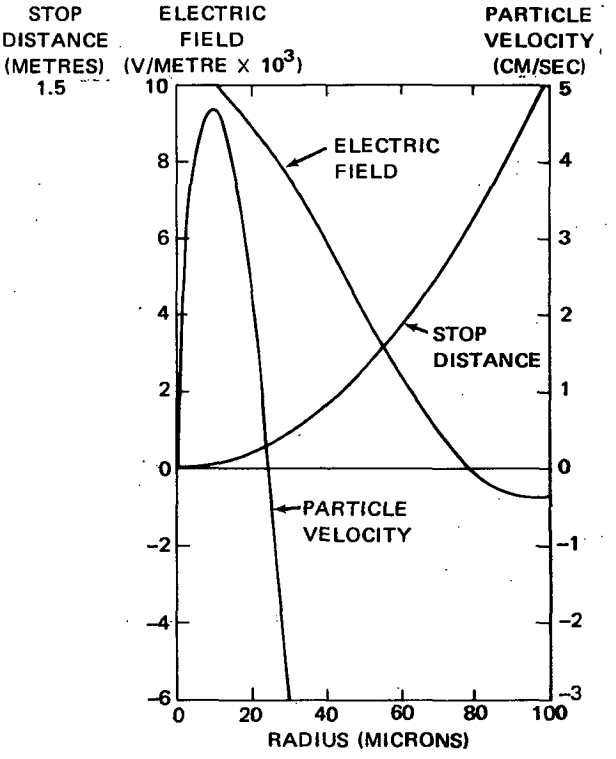

FIGURE 5

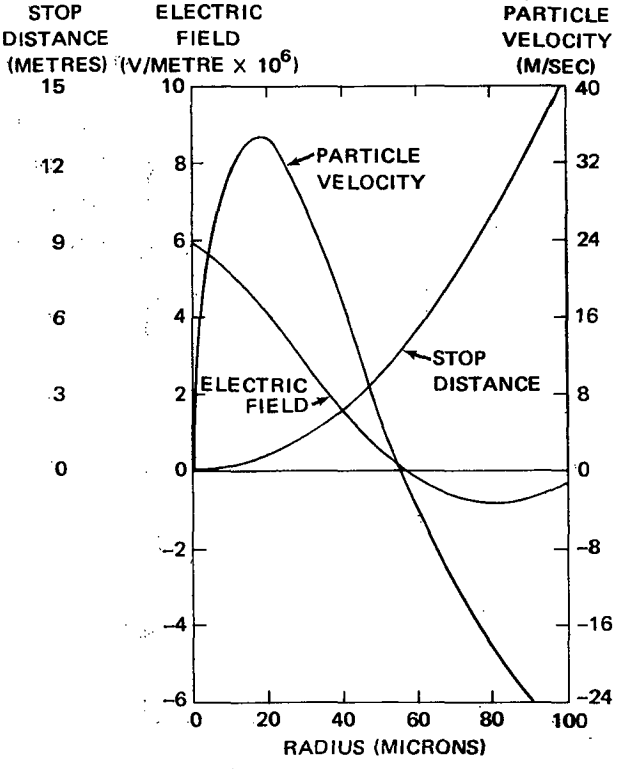

FIGURE 6

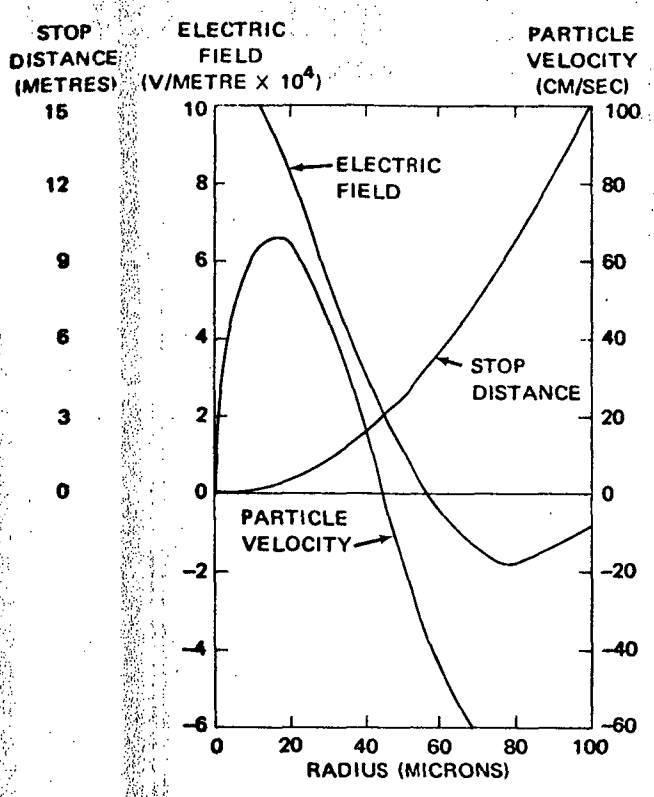

FIGURE 7

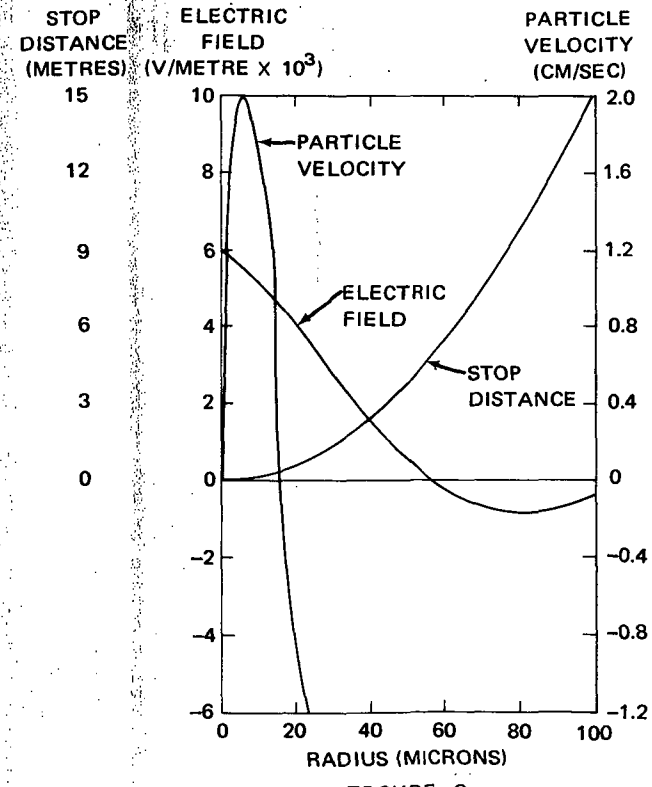

FIGURE 8

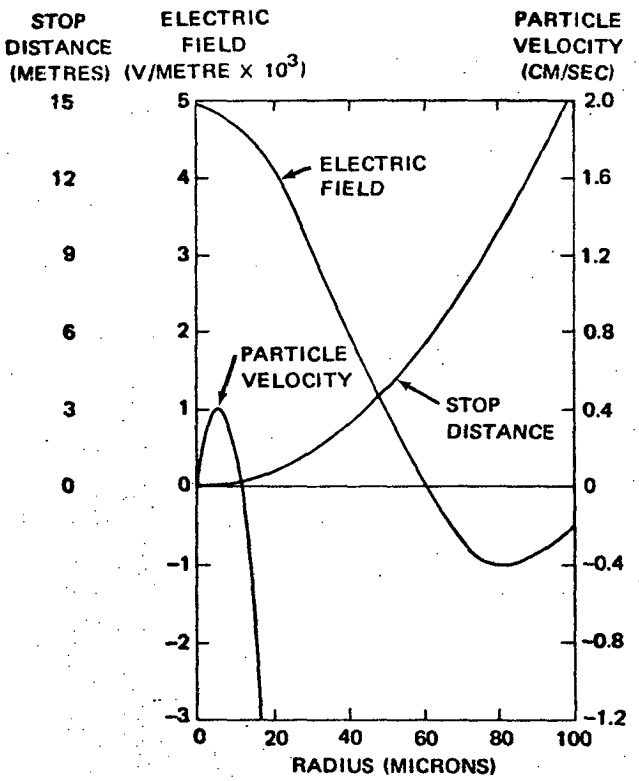
STOP DISTANCE (METRES)
ELECTRIC FIELD (V/METRE X 10^3)
PARTICLE VELOCITY (CM/SEC)
15
12
9
6
3
0
5
4
3
2
1
0
-1
-2
-3
2.0
1.6
1.2
0.8
0.4
0
-0.4
-0.8
-1.2
ELECTRIC FIELD
PARTICLE VELOCITY
STOP DISTANCE
0
20
40
60
80
100
RADIUS (MICRONS)

FIGURE 9

A COMPUTER PROGRAM FOR FOG PREDICTION AT PORTLAND, OREGON

by

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Research Department

ABSTRACT

The results given from two studies of fog prediction at Portland, Oregon have been translated into a program for operation on a minicomputer. Although this program is quite short, with few data inputs, it shows promise as a first step in developing a more complete program and in developing similar programs for other fog prone locations.

BACKGROUND

The use of minicomputers in research laboratories has increased rapidly in the past few years. This is due to the devlopment of easy-to-use programming languages such as FORTRAN, BASIC, and ALGOL, and also due to the large decreases in costs made possible by medium and large-scale integration of computer circuitry. By use of prepared programs, data may be reduced and answers obtained in seconds, which here-to-fore involved long periods of tedious calculations.

There are a number of problems in weather research and weather modification which can profitably utilize the high speed and accuracies obtained by use of digital computers. Once a program is written and debugged, it can be loaded and operated in a few seconds, and the results obtained.

There are two general methods used in making weather predictions: (1) A numerical modeling of atmospheric processes, wherein initial atmospheric conditions are set and then thermodynamic and physical equations are used to predict the developments of changes, and (2) objective methods in which knowledge and past experience in a local area are used in predictions of future local conditions. The first method involves very complex mathematical routines and quite large computer systems. There have been tremendous advances in the use of this method within the past few years, but further refinements depend on faster and larger machines (Ref. 1).

STATEMENT OF PROBLEM

The Earth and Planetary Sciences Division, Code 602 of Naval Weapons Center has been conducting experimentation on weather modification and clearing of warm fog at Arcata, California for the past several years. This work would be greatly helped by having a systematic method of predicting the occurrence of fog, since efficient scheduling of operations would greatly help in time and cost factors. Although the present study is not directly applicable to conditions at Arcata, it is of sufficient interest as a method in itself, and the predictors examined in this study may indicate useful areas of investigation of Arcata fogs.

PROCEDURE

Black (Ref. 2) made a systematic examination of some thirty meteorological parameters corresponding to fog occurrences during the month of October (1957-1964) at Portland, Oregon. These parameters were plotted according to the fog conditions: occurrence of ceilings less than 300 ft. and visibilities less than one mile during the period of 2200 LCT through 1000 LCT.

By examination of this data, along with wind conditions, station pressures etc., Black developed a "forecaster's check list" and a series of eight charts from which predictions could be made during the month of October. The charts are also valid for the last two weeks of September and the first two weeks of November.

An evaluation made as part of this study showed correct forecasts from 82 to 94% of the time, depending on the data used.

A follow-up of this study was made by Elkins (Ref. 3). In this study Elkins continued the study initiated by Black and expanded it to include the months of September through February.

It was found that the number of predictors could be reduced to five; the Portland 2200 LCT temperature and dewpoint, the Salem 0000Z 950-millibar temperature and dewpoint, and the Portland maximum temperature during the day. By using these values to enter a nomogram, the probability of fog occurrence is found.

As noted by Elkin, unstable conditions will weaken the validity of this method of fog prediction, so that weather fronts or strong pressure gradients need to be excluded.

The objective of the present study then is the reduction to a computer program of Elkins' predictors and nomogram.

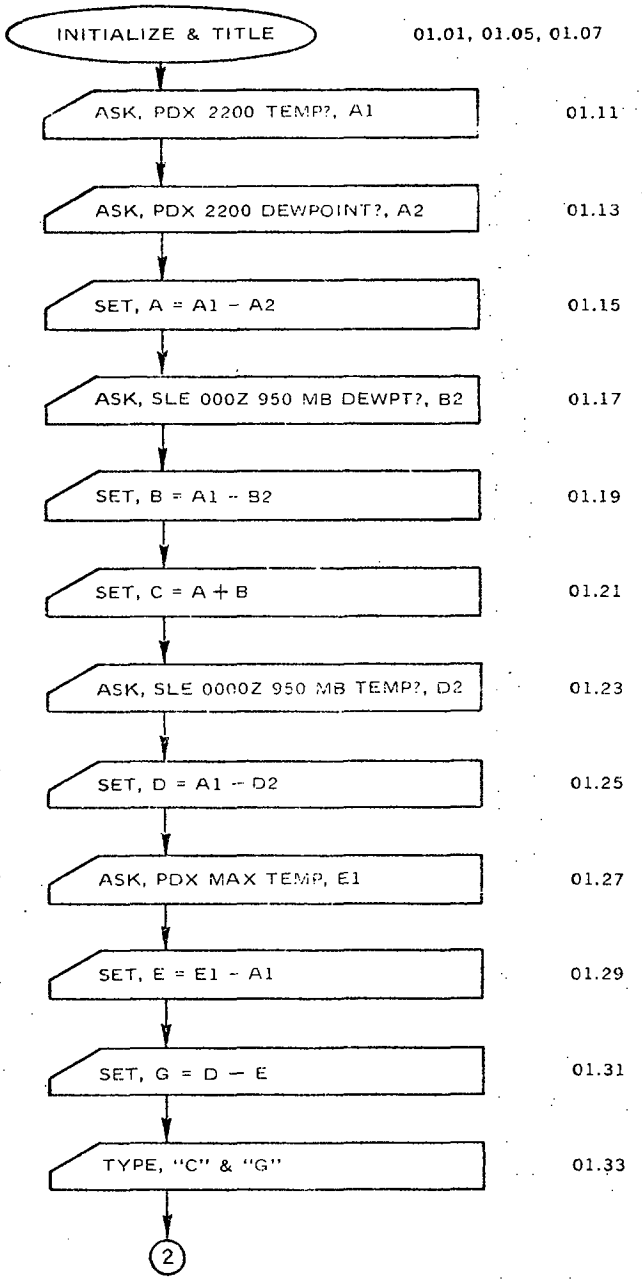
METHODS

The computer used in the formulation of this program is the Digital Equipment Company standard PDP-8 with 4K memory core. The computer language is FOCAL*, which is a conversational language very similar to BASIC** in structure and operation.

Operations and instructions for this language used in the program are: ASK, for teletype keyboard input of data; TYPE, for printout; SET, for defining equations, variables, and constants; IF, for a decision branch. The commands may be abbreviated to the first letter, as they are done here, to conserve memory storage space. The program can easily be translated to BASIC or FORTRAN.

*Trademark, Digital Equipment Co.
**Trademark, Dartmouth College

A flow chart illustrating the program steps is shown as Figure 1, and the program itself is listed in Figure 2.



FLOW CHART - Figure 1

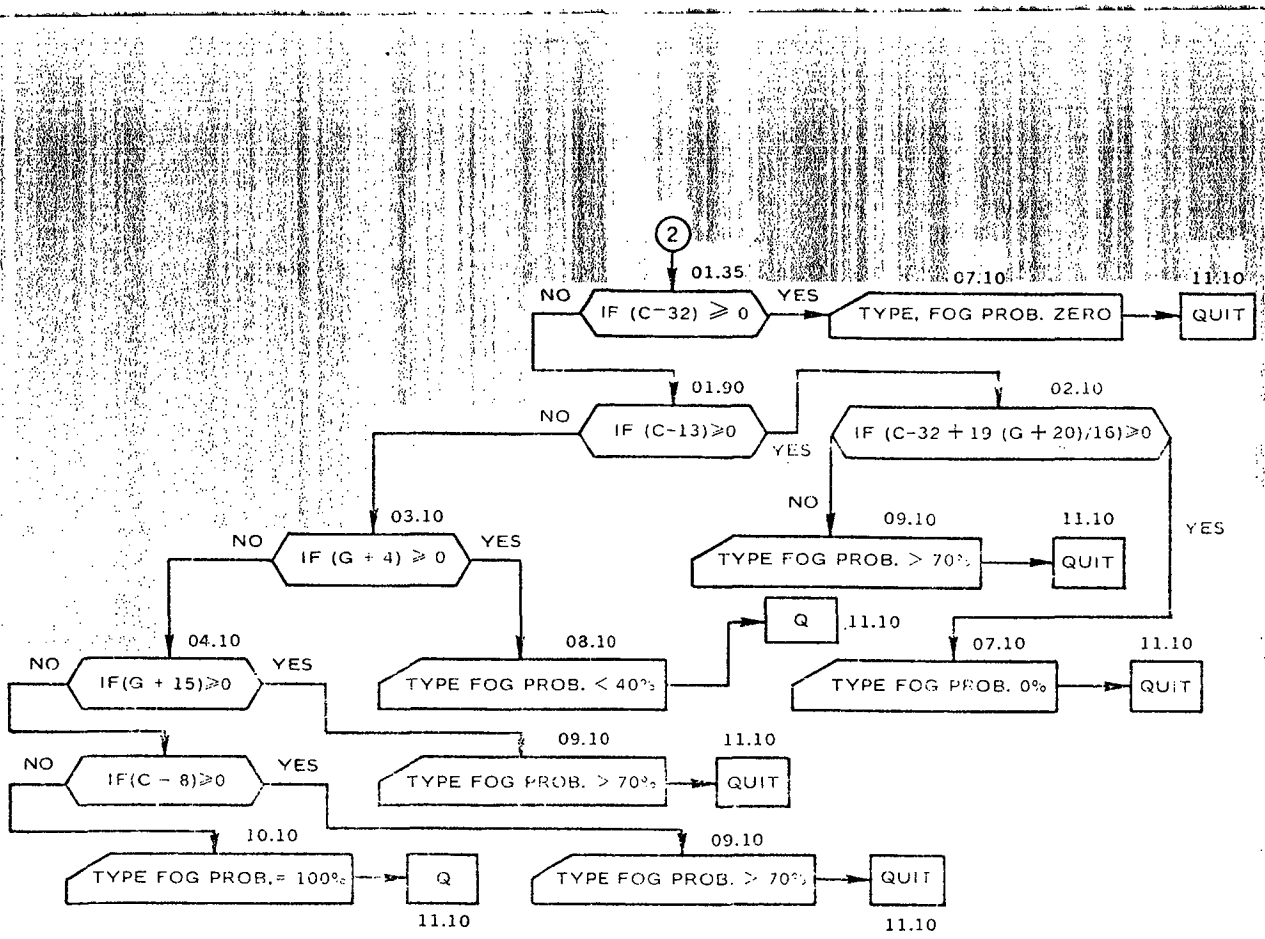


FIGURE 1 - continued

FLOW CHART SHOWING THE STEPS IN THE FOG PREDICTION PROGRAM

An example of a program run is shown in Figure 3. After the "GO" command the program types the first three lines and asks for the Portland temperature and dewpoint for 2200 LCT, and then the Salem 950 millibar dewpoint and temperature for 000Z. It then asks the Portland maximum temperature (all temperatures are degrees Farenheit). With this information it computes the values of "C" and "G", prints these out, and goes through the process of locating the proper block of the nomogram by use of the IF statements. The point found by the example is shown on Figure 5. The worksheet computation is shown in Figure 4.

```
C-FOCAL,1969

01.01 T ! "PORTLAND, OREGON FOG PREDICTION PROGRAM",!!
01.05 T "IF FRONT OR TROUGH WITHIN 100 MILES, OR IF STRONG",!
01.07 T "EAST-WEST PRESSURE GRADIENT,USE ANOTHER METHOD",!!
01.11 A "PDX 2200 TEMP?",A1,!
01.13 A "PDX 2200 DEWPOINT?",A2,!
01.15 S A=A1-A2
01.17 A "SLE 00002 950 MB DEWPOINT?", B2,!
01.19 S B=A1-B2
01.21 S C=A+B
01.23 A "SLE 00002 950 MB TEMP?",D2,!
01.25 S D=A1-D2
01.27 A "PDX MAX TEMP",E1,!
01.29 S E=E1-A1
01.31 S G=D-E
01.33 T "C",C,!,"G",G,!
01.35 IF (C-32) 1.9,7.1,7.1
01.90 IF (C-13) 3.1, 2.1, 2.1

02.10 IF (C-32+19*(G+20)/16) 9.1, 7.1, 7.1

03.10 IF (G+4) 4.1, 8.1, 8.1

04.10 IF (G+15) 5.1, 9.1, 9.1

05.10 IF (C-8) 10.1,9.1, 9.1

07.10 T "FOG PROBABILITY= ZERO",!; GOTO 11.1

08.10 T "FOG PROBABILITY=<40%",!; GOTO 11.1

09.10 T "FOG PROBABILITY=>70%",!; GOTO 11.1

10.10 T "FOG PROBABILITY= 100%",!; GOTO 11.1

11.10 QUIT
*
```

FIGURE 2

```
*
GO

PORTLAND, OREGON FOG PREDICTION PROGRAM

IF FRONT OR TROUGH WITHIN 100 MILES, OR IF STRONG
EAST-WEST PRESSURE GRADIENT, USE ANOTHER METHOD

PDX 2200 TEMP?:60

PDX 2200 DEWPOINT?:41

SLE 00007 950 MB DEWPOINT?:25

SLE 00007 950 MB TEMP?:32

PDX MAX TEMP:72

C=    54.0000
G=    16.0000
FOG PROBABILITY= ZERO
*
```

FIGURE 3

WORKSHEET

NOTE: Check the following synoptic situation before using this method:

1. Front or trough within 100 miles of Portland? YES___ NO X
2. East-west pressure gradient along Columbia Gorge? YES___ NO X

IF YES, DO NOT USE THIS METHOD. IF NO, CONTINUE.

1. PDX 2200P TMF 60 (Deg F)
2. PDX 2200P Td 41 (Deg F)

1-2 = A 19

3. PDX 2200P TMP 60 (Deg F)
4. SLE 0000Z 950MB Td 25 (Deg F)

3-4 = B 35

A 19

+ B 35

C 54

5. PDX 2200P TMP 60 (Deg F)
6. SLE 0000Z 950MB IMP 32 (Deg F)

5-6 = D 28

7. PDX MAX TMP 72 (Deg F)
8. PDX 2200P IMP 60 (Deg F)

7-8 = E 12

D 28

- E 12

= G 16

Enter nomogram with C and G to determine forecast.

FIGURE 4

RESULTS AND CONCLUSIONS

Although this program is short, the principle illustrated may be useful as a basis for similar work in other locations, or in developing programs for more complex situations.

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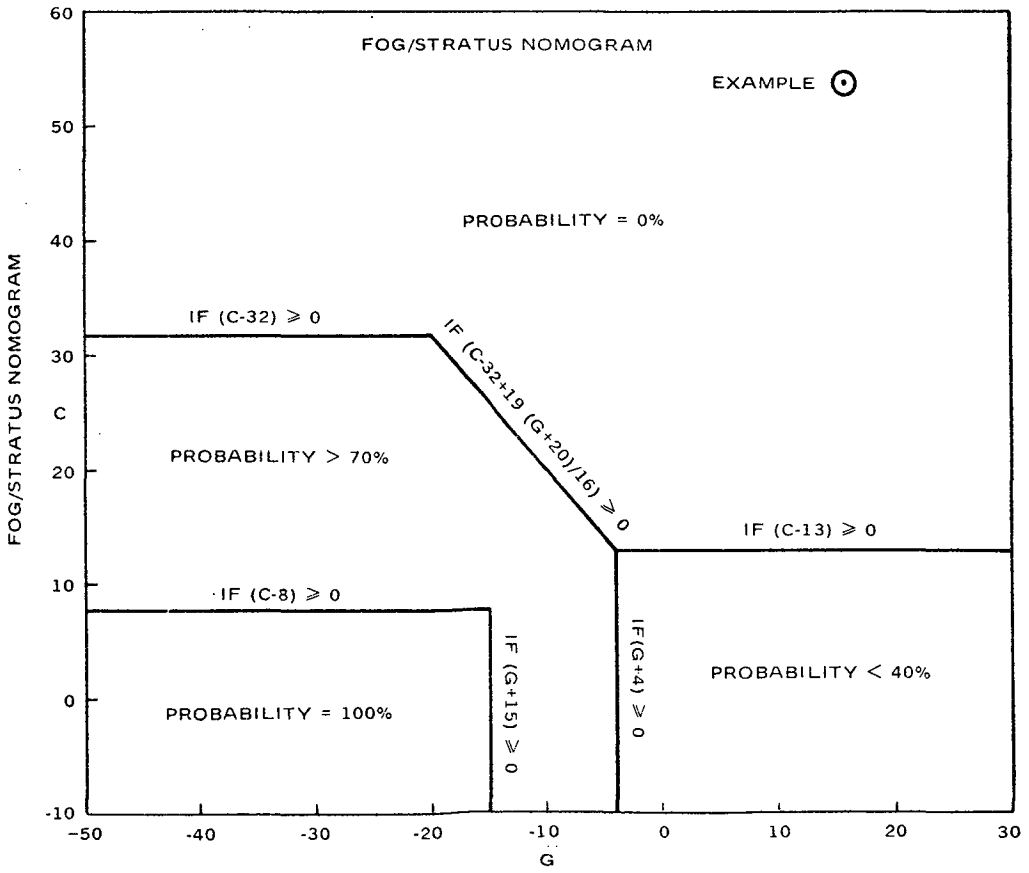

FIGURE 5

RESULTS FROM COMPARISONS BETWEEN THE FIELD APPLICATIONS OF AgI-NaI and AgI-NH_4I SOLUTIONS IN AIRBORNE GENERATORS ON A HAIL SUPPRESSION PROGRAM IN KENYA

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1. INTRODUCTION

The history of modern weather modification research and operations in the United States and abroad began with the near simultaneous use of solid carbon dioxide and silver iodide smoke particles as the most common freezing nuclei. Although carbon dioxide has been used on several cloud seeding projects throughout various areas of the world, its popularity has diminished over the years. A portion of this rejection can be attributed to storage problems, a short shelf life, processing difficulties and the requirement for relatively large volumes of material. Thus, a major portion of nucleation research conducted during the past several years has been directed toward the generation of silver iodide particles.

In the early years of weather modification programs, acetone burners occupied the most favorable position in most operational and research programs. However, a wide variety of other devices were also developed which utilized charcoal, string, coke, paper, wood chips and corn cobs. In most all cases the materials were impregnated with solutions formed by solubilizing silver iodide-sodium iodide combinations in acetone. These materials were dried and burned, sometimes in rather ingenious mechanical devices. Efficiencies in terms of effective nuclei per gram of silver iodide were seldom considered important to the field program applications. In spite of the numerous attempts to develop devices which utilized impregnated materials, most researchers continually returned to the acetone burner.

In the mid-1950's, pyrotechnic generation of silver iodide gained importance throughout a number of operational weather modification programs in the United States. Early formulations were compounded by the simple addition of silver iodide to a variety of standard flare mixes. Products of combustion were complex and little understood. In recent years, one notes the development of improved pyrotechnic seeding devices with more definitive investigations of combustion products largely through the extensive research efforts of the Naval Weapons Center at China Lake, California (St. Amand, Finnegan, et al, 1970-1971). As applications programs expanded, the use of pyrotechnic generated silver iodide particles gained universal acceptance and today they are standard devices in the kit of weather modification tools.

In some early attempts to produce silver iodide particles, some

investigators (Vonnegut, 1949) exploited the fact that silver iodide is soluble in mixtures of ammonium iodide or alkali iodide and acetone. For reasons that are not completely clear, the use of ammonium iodide was abandoned in favor of sodium iodide as a primary solubilizing agent. This change may be the most important single act which has influenced nucleation behavior and the results from field experience during the following 20 year period.

The behavior of ice nuclei depends, in a large measure, on physical properties, chemical composition and their residence within any particular environment. Researchers (St. Amand, Blair, Finnegan, et al, 1970-71) have suggested that complexes of silver iodide and alkali iodides can be considerably altered by a warm moist environment. It further appears that relatively pure silver iodide nuclei produced by ammonium iodide solutions are unaffected by similar environmental conditions. This fact suggests that results from treatment of clouds by introduction of silver iodide in the warm inflow regions at cloud base might be significantly enhanced if the nuclei are generated from solutions where ammonium iodide is used as the solubilizing agent. In any case, this possibility has caused an extensive reexamination of liquid fueled silver iodide generators and their potential as a primary seeding device for applied research and operational programs.

During the March-August period in 1971, approximately 400 potential hail producing cumulus clouds in Kenya, East Africa, were treated with either the NaI-2AgI or NH_4I-2AgI solutions. Material was introduced by aircraft in the strong inflow area near cloud base at temperatures ranging from +14C to +5C. In the following sections the applications are discussed and comparative effectiveness is summarized.

2. KENYA HAIL SUPPRESSION PROGRAM

In an area approximately 120 miles northwest of Nairobi, Kenya, at an elevation of 7,000 ft. msl, some 45,000 acres of select tea are under production. From this growing area, the land slopes away to the west toward Lake Victoria at 3,500 ft. msl and rises eastward 50 miles to higher mountain country where peaks exceed 10,000 ft. msl. Average annual rainfall is approximately 75 inches and hail is noted somewhere over the tea estates on more than 200 days per year. The operational area is shown in Figure 1.

The Kenya Hail Suppression Program was initiated in 1967. In addition to the primary objective of reducing hail damage on tea plants, the project design includes attempts to augment rainfall on those days when the threat of hail is minimal. This operational cloud seeding program involves the aerial application of silver iodide to cumulus clouds which move eastward from the higher elevation terrain across the tea estates toward Lake Victoria. All material applications are accomplished at cloud base in the strong inflow areas identified as being important to the specific volumes of clouds which give birth to, and allow growth of, hailstones. Primary equipment in the operational unit includes three cloud

seeding aircraft and a 3cm radar system.

Throughout the past four and one-half years of operation, silver iodide has remained the only nucleating agent available to the project. The generation of silver iodide freezing nuclei was initially limited to pyrotechnic devices. In the past 18 months, liquid fueled airborne generators utilizing solutions of NH_4I-2AgI or NaI-2AgI, have been added to each seeding aircraft. To date, cloud seeding has been accomplished on more than 950 operational days. During this period, silver iodide has been applied to more than 3600 individual cumulus clouds.

3. THE FIELD TESTS

During the six months period March-August 1971, approximately 400 potential hail producing cumulus clouds were treated with either the NaI-2AgI or NH_4I-2AgI seeding solution. For the working solution, silver iodide concentration was maintained at 2.5% by weight in acetone. The use rate of solution during seeding operations was fixed at 2.0 gallons per hour per generator. Table 1 shows the composition of the stock solution as prepared before dilution for use in the airborne generators.

TABLE 1.

Silver Iodide Stock Solution

NaI-2AgI	NH_4I-2AgI
25.0% AgI	25.0% AgI
8.0% NaI	7.7% NH_4I
3.0% H_2O	3.0% H_2O
64.0% Acetone	64.3% Acetone

The airborne generators used on this project are modifications of several generations of units developed during the past 20 years of aircraft seeding operations. Fundamentally, the units contain three sections: (1) A forward tank section which has a capacity of 7.2 gallons of liquid, (2) a center section which contains the valve controls, igniter coil assembly and liquid spray nozzle, and (3) the aft burner section which acts as the flame chamber and contains the spark gap igniter assembly.

Under aerial operation the flame temperature inside the burner chamber is approximately 750C. The actual generators used during these operations have not been tested for efficiency but similar generators using AgI in both NaI and NH_4I solutions have been tested at the South Dakota School of Mines and Technology in Rapid City, South Dakota (Donnan, et al - 1970) The results of these tests show efficiencies of both solutions in terms of effective nuclei per gram of AgI ranging from about 10^{10} at -5C to 5 x 10^{14} at -20C.

During the six months applications period, the cloud types encountered were not different from the range of clouds experienced during previous periods of operation. There is a unique persistence in daily cumulus activity over the operational area. Before noon, small cumulus are noted to form over the higher terrain east of the tea estates. This results from the low level transport of moisture from Lake Victoria on the west. As the day progresses and heating increases, clouds continue their vertical development until they reach altitudes sufficient for movement away from the higher land and out across the target area. Table 2 shows some of the cloud parameters at time of treatment in each of the seeding solution categories.

TABLE 2

Cloud and Seeding Data

Parameters at time of Seeding	NaI-2AgI	NH_4I-2AgI
Total Clouds Seeded	178	222
Average gms. AgI per cloud	183	177
Average Cloud Base Elevation	12,100 msl	12,300 msl
Cloud Base Temp. Range	+4C - +12C	+5C - +14C
Average Cloud Temp.	+10C	+10C
Radar Echo Top Elev. Range	21,400 to 42,500 msl	20,800 to 41,200 msl
Average Radar Echo Top Elev.	29,200 msl	28,800 msl

4. RESULTS AND CONCLUSIONS

For many years it has been apparent that the product of acetone burners using AgI and sodium iodide is some complex of these two compounds rather than a relatively pure crystal of silver iodide. Various aspects of this consideration have been discussed at some length by Mason and Hallet (1956), Vonnegut (1957), Koenig (1964), R. G. dePena (1964), St. Amand (1967) and Burkhardt (1970). It is sufficient to point out here that such a AgI-NaI complex is hygroscopic and its behavior as a nucleant is largely dependent upon the history of the material prior to its introduction into the cloud region colder than -5C.

When ammonium iodide is used as a solvation agent for silver iodide,

the NH_4I is destroyed after sublimation yielding water, nitrogen, free iodine and a few other species. The presence of free iodine protects the AgI from disassociation and a relatively pure crystal of silver iodide remains. This product is not hygroscopic and the resultant nucleation properties do not appear to be as significantly altered by exposure to warm, moist regions of cumulus clouds.

Throughout the tea growing area of Kenya, when a hail instance is noted by the estate managers, the damage is assessed as pounds of finished tea. Inasmuch as the crop from each estate is harvested every ten-day period, the new tea leaves provide a near infinite platform of hail indicators. Throughout this test period, all hail instances from treated cumulus cells passing over the estates were logged as part of the normal reporting scheme. A tabulation of hail damage noted during this experimental period is shown in Table 3.

TABLE 3

Hail Damage Data

	NaI-2AgI	NH_4I-2AgI
Number of Clouds Seeded	178	222
Non-damaging hail instances reported	26	11
Damaging hail instances reported	28	7
*Average hail damage (lbs. per hail instance)	4930	1220

*Based only on those hail instances which produced damage

Instances of hail which produce no damage as well as those where damage was noted, are shown in the above table. In both of these categories, the numbers of hail instances are higher for those cells treated with the NaI-2AgI system. Of greater significance is the fact that damage per hail instance, when the NH_4I-2AgI system was used, is much less than in the case of NaI-2AgI treatment. Note that these figures are based only on those instances which produce damage and do not consider those hail instances which produce little or no damage.

From these comparisons there appears a strong suggestion that, (1) the numbers of both damaging and non-damaging hail instances is significantly less when cloud treatment utilizes the NH_4I-2AgI solution, (2) the damage per hail instance is also significantly less when this solution is used for treatment for treatment, and, (3) the NH_4I-2AgI solution

appears about 75% more effective than the NaI-2AgI solution when the application procedure is limited to dispersal at cloud base in a temperature regime warmer than +4C.

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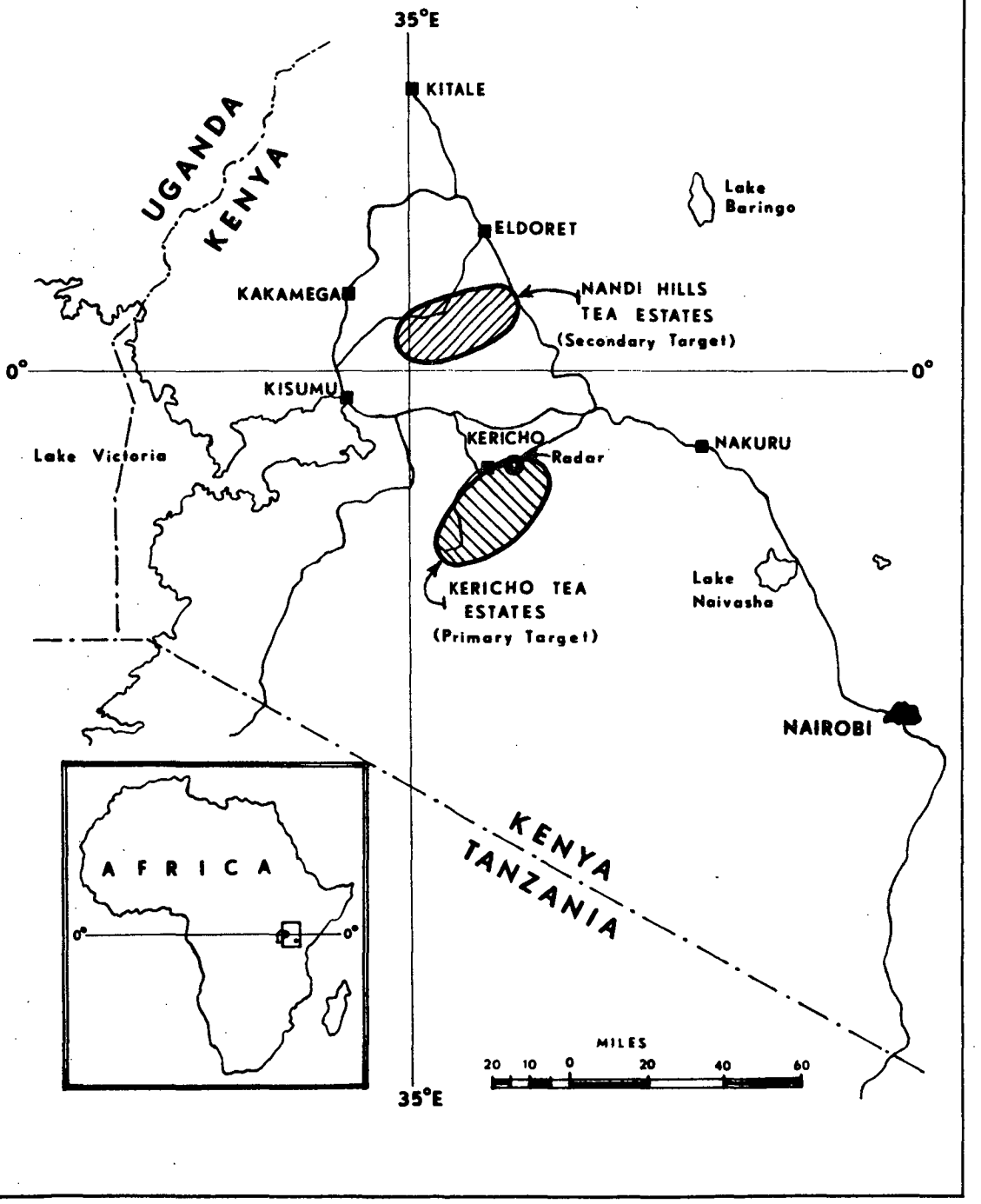
FIGURE 1.

KENYA PROJECT AREA



RESULTS FROM THE USE OF LW-83 PYROTECHNIC SEEDING DEVICES ON OPERATIONAL OROGRAPHIC CUMULUS PROGRAMS IN AFRICA AND CALIFORNIA

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1. INTRODUCTION

For the past several years, pyrotechnic generated silver iodide has occupied a strong position in cloud seeding applications programs throughout the world. Examples of operational and applied research efforts include programs in California, Colorado, Florida, North Dakota, Oklahoma, South Dakota, Texas, Utah, Australia, Canada, France, India, Israel, Italy, Kenya, Philippines, Russia, South Africa, Switzerland, and a few countries in South America.

Variations in pyrotechnic formulations have been exceeded only by the number of storms available for treatment and the many theories related to storm behavior. Early formulations were developed by the simple addition of silver iodide or silver iodate to standard road flare mixes composed of potassium nitrate, strontium nitrate, kerosene, sulphur, beeswax and wood fragments. The precise products of combustion of these early units were difficult to determine and results from their use were clouded by the chemistry of complexing compounds. Little consideration was given to the importance of these combustion products in terms of nucleation efficiencies within clouds chosen for treatment. Further, practically no consideration was given to the locations in or near clouds for the dispersal of material.

In recent years we have seen the development of improved pyrotechnic seeding devices and more definitive investigations of combustion products and nucleation. As applications programs increased their use of pyrotechnic cloud seeding devices, there began to emerge a pattern of confirmation with respect to the relationships of nucleation theory, treatment technology, particle efficiencies and apparent overall pyrotechnic effectiveness. This pattern gains considerable strength as new programs develop and investigators address themselves specifically to these important relationships.

During the May-September period in 1971, a number of LW-83 pyrotechnic seeding devices were added to the operational phases of a rain stimulation program over the Kings River in California and a hail suppression program in Kenya, Africa. Developed for the Naval Weapons Center at China Lake in California, these units were furnished for purposes of comparing their operational effectiveness with other type pyrotechnic units as well as the airborne AgI-NaI liquid fuel generators.

2. PYROTECHNIC SEEDING DEVICES

Three different type pyrotechnic seeding devices were used in the applications programs during the period selected for examination of apparent result. These were the LW-83 units supplied by the Naval Weapons Center at China Lake, California; the WM-105 units supplied by Olin Corporation at East Alton, Illinois; and the 600-001 units supplied by Colspan in Boulder, Colorado. The compositions and silver iodide dispersal rates are shown in Table 1. Although the fundamental compound in the pyrotechnic mix is silver iodate, the dispersal rates are given in grams per minute of effective silver iodide. Comparative efficiencies in terms of active nuclei per gram of silver iodide are shown in Table 2.

3. APPLICATIONS PROGRAMS

3.1 Kings River Program

Initiated in 1954, the Kings River Weather Modification Program is designed to increase precipitation over a 1600 square mile mountain watershed in the Southern Sierra Range of California. During the seasonal periods October through April, the project has operated each year since its inception. In June 1966, the Atmospheric Water Resources Research group, Fresno State College Foundation, under contract with the Bureau of Reclamation, began a program of weather modification research dealing with the feasibility of seeding summer cumulus over a number of high altitude sub-basins within and adjacent to the Kings River watershed. After three years of randomized single cloud and non-randomized area seeding experiments, Project Sierra Cumulus evaluation produced strong evidence of positive benefits from this program.

In 1971, the Kings River Conservation District added summer orographic cumulus seeding to their seasonal Kings River program in those years when irrigation water shortages were anticipated. This summer seeding program has provided one of the basic operational platforms for the introduction and assessment of various pyrotechnic seeding devices. Location of the Kings River area is shown in Figure 1.

3.2 Kenya Hail Suppression Program

Some 120 miles northwest of Nairobi, Kenya, in two areas which total about 1500 square miles, approximately 45,000 acres of select tea are in production. From Lake Victoria the land slopes upward toward the east to 7,000 ft. msl where this tea is produced. The land continues its rise further eastward another 50 miles to several mountain peaks over 10,000 ft. msl. Over the tea estates hail is recorded on the average of more than 200 days per year.

Initiated in 1967, the Kenya Hail Suppression Program is designed to suppress hailfall over two target areas which total approximately 1500 sq. miles. This operational cloud seeding program involves the aerial application of silver iodide to select cloud base locations thought to be

relevant to those specific volumes of clouds which give birth to, and allow growth of hailstones. Because of the large number of hail days spread throughout each month of the year, this operational program offers another unique opportunity for testing a variety of cloud seeding devices. The most severe hail areas in the United States only offer about 1/8th the total opportunities per year experienced in this area of Kenya. Location of the Kenya Project is shown in Figure 2.

4. METHODS OF EVALUATION

4.1 Kings River Project Area

For the past 17 years, the winter seeding portion of the Kings River Project has been analyzed by a variety of techniques. Foremost among these methods has been the statistical analysis of annual streamflow data from the Kings River and adjacent watersheds having similar hydrologic characteristics. Results from this particular investigation have indicated an average annual streamflow increase between 6 and 10%.

For summer seeding in Project Sierra Cumulus, the evaluations have been largely based on hydrologic model analyses of streamflows from upper watershed sub-basins within and adjacent to the Kings River. This technique is designed to use direct runoff from summer precipitation as an index to the effect of cloud seeding. In order to avoid the complexities of rain on snow, the analysis has been restricted to that period subsequent to the end of substantial snowmelt runoff. Multiple correlation coefficients have been as high as 0.960 in some of the basin comparisons.

Results from individual storm comparisons have indicated apparent increases in runoff on the order of 33% with statistical significance above the 90% level. For this reason, the chances appeared excellent for determining effectiveness of various cloud seeding devices applied on summer cumulus over the Kings River.

4.2 Kenya Project Area

One of the most powerful indicators which can give us a reasonable estimate of effects from seeding appears to be an assessment of hail damage to the tea plant. Inasmuch as tea is harvested from each bush every 10-15 days, growth and production curves related to each tea estate provide a means of estimating loss in the field after each hail instance. The tea bushes act as nearly infinite hail indicators with each leaf responding in some way to the individual hailfall.

Over the past 4½ years of weather modification in the Kenya area, a rather exhaustive examination has been conducted on nearly 1800 hail instances from seeded and non-seeded cumulus cells. The results from these analyses have produced evidence of hail damage reduction in excess of 60%, with statistical significance above the 90% level.

On this project alone, more than 3000 potential hail clouds have

been seeded with pyrotechnic devices or airborne liquid fuel generators containing either AgI-NaI or AgI-NH_4I solutions. It has provided a reasonably sound basis for examining the effectiveness of materials and applications techniques.

5. RESULTS FROM COMPARATIVE TESTS

5.1 Applications in Kenya

During the May-September period of 1971, the aircraft applied a total of 120 pyrotechnic cloud seeding devices to 76 thunderstorms having a high potential for producing hail damage to tea plants. Forty-eight of these units were the LW-83 type. Airborne liquid fuel generators were used on 12 additional cumulus cells having similar growth characteristics.

The number of hail instances from the passage of all treated cumulus cells over the target was logged as part of the normal reporting scheme developed for the tea estate managers. Comparisons of use and effectiveness are shown in Table 3.

From the 88 treated cumulus cells suspected of being potential hailers, 27 hail instances of hail were reported by the various tea estates. In four cases, a single cloud was noted to produce two hail instances. All the rest of the reported instances were identified as resulting from separate cumulus cells.

Shown on the last line of Table 3, is the average amount of damage in pounds of tea per hail instance. These damage figures are calculated by the tea estate managers from differences between the average estate production from the three plucking rounds just prior to damage and the production from the next plucking round following a given hail instance.

In terms of tea damage per hail instance, resulting from this preliminary field test, the LW-83 pyrotechnic seeding units would appear to be about twice as effective as the 600-001, six times as effective as the AgI-NaI solution, and more than eight times as effective as the WM-105 units. It should be noted these figures are not intended to imply a recommendation for any particular type seeding device. They are presented only as unweighted figures from a very limited experiment without benefit of statistical design.

5.2 Applications on the Kings River

During the 1968 and 1971 summer seasons on the Kings River in California, a total of 67 individual cumulus clouds were seeded with 114 pyrotechnic units of the 600-001, LW-83 and WM-105 types. Silver iodide amounts ranged from 130 grams to 270 grams per cloud.

Following the snowmelt season, streamflow runoff resulting from seeded cloud precipitation was examined for all cases where high altitude sub-basins produced measurable flow. These target sub-basins included

Bear Creek near Lake Thomas A. Edison (San Joaquin Basin), the San Joaquin River at Miller Crossing, North Fork of the Kings River below Meadowbrook and Marble Fork of the Kaweah River at Potwisha.

The areas of these high elevation sub-basins, and the average runoff per square mile after snow melt season, are shown in Table 4. Comparisons of pyrotechnic use and effectiveness from this investigation are shown in Table 5.

Measurements of streamflow runoff were assessed during the periods when the 67 treated clouds produced precipitation over the sub-basins. Shown on the last line of Table 5 are the average streamflow runoff figures in acre feet per square mile per seeded event for the three type pyrotechnic seeding devices utilized during this activity. In terms of the streamflow approach, the LW-83 unit appears slightly more effective than the 600-001 and almost twice as effective as the WM-105 unit. Again, these data are presented only for general interest and no statistical significance is implied.

FIGURE 1

KINGS RIVER PROJECT AREA
SIERRA NEVADA RANGE IN CALIFORNIA

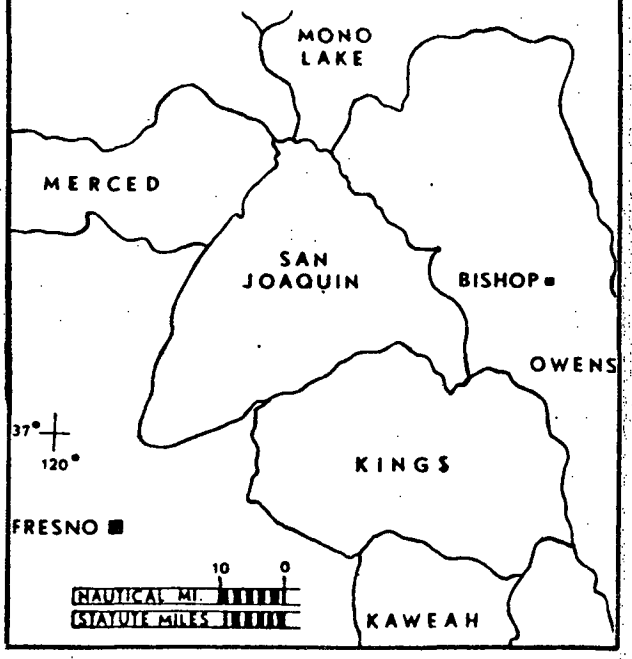

Table 1.

Composition and dispersal rate

LW-83	600-001	WM 105
78% $AgIO_3$	17% $AgIO_3$	53% $AgIO_3$
5% Mg	50% NH_4IO_3	12% Mg
11% Al	15% Mg	6% Al
6% Binder	7% Al	19% KIO_3
	5% Li_2CO_3	10% Binder
	6% Binder	
200 gms min^{-1}	8 gms min^{-1}	30 gms min^{-1}

TABLE 2

Efficiency Analysis

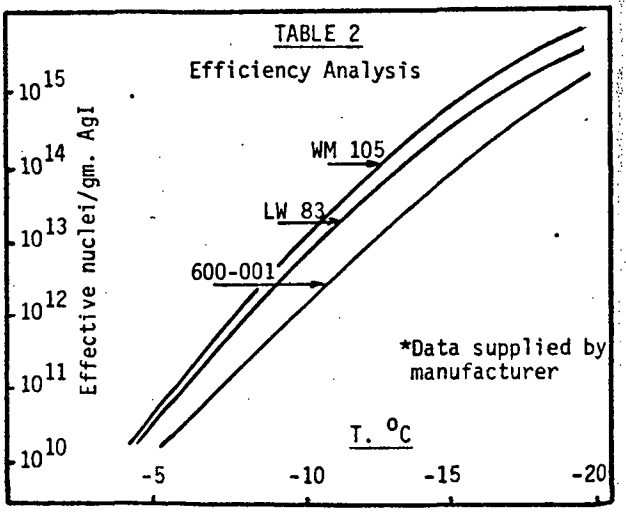

FIGURE 2

KENYA PROJECT AREA

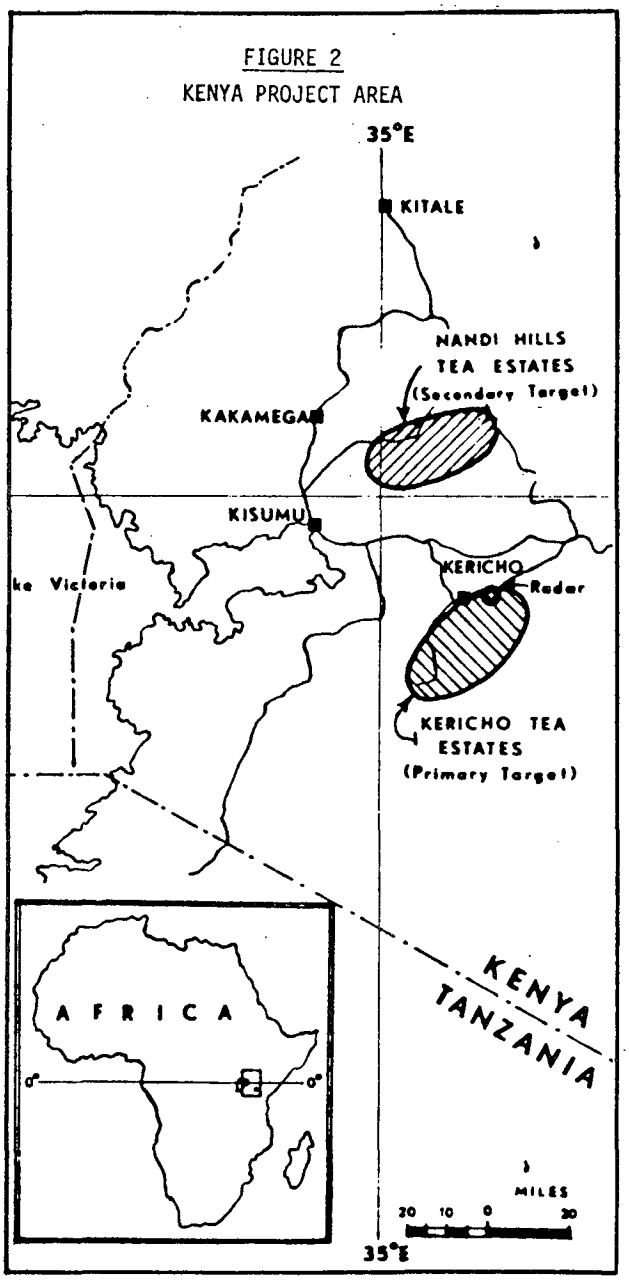

TABLE 3.

Comparison of Cloud Seeding Devices

- Kenya Project -

	WM-105	LW-83	600-001	AgI-NaI
Pyrotechnics used:	32	48	40	-
No. of clouds seeded:	32	24	20	12
Gms AgI per cloud:	270	200	130	168
Hail instances:	14	3	7	3
Average hail damage: (lbs. per hail instance)	7840	960	1870	5760

TABLE 4.

Sub-Basin Physical Characteristics

- Sierra Range in California -

Sub-Basins	Area (mi^2)	*Ave.Runoff (A.F. mi^{-2})
Bear Creek near Lake Thomas A. Edison	53.5	19.4
San Joaquin River at Miller Crossing	25.4	16.5
North Fork Kings River below Meadowbrook	37.7	16.1
Marble Fork Kaweah at Potwisha	51.4	7.0

*Figures for 13-year period 1952-1964

TABLE 5.

Comparison of Cloud Seeding Devices

- Kings River Project -

	WM-105	LW-83	600-001
Pyrotechnics Used	20	56	38
No. of clouds seeded	20	28	19
Gm AgI per Cloud	270	200	130
Ave. Streamflow Runoff* (A.F. mi^{-2} per seeded event)	12.7	23.6	19.8

*Average from all sub-basin flows associated with the use of each particular pyrotechnic seeding device.

THE AIRBORNE SEEDING OF SIX TORNADOES

Thomas J. Henderson
and
William J. Carley

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1. INTRODUCTION

For the past five or six years, the possibility of seeding a tornado by the aerial application of silver iodide has intrigued the operational crews on a number of weather modification projects in the United States and abroad. During the 1970 and 1971 applications programs of hail suppression in Texas and Kenya, weather conditions developed which permitted cloud base seeding in the immediate vicinity of tornadoes. These storm conditions presented a unique opportunity to ascertain, (1) some of the safety aspects related to aircraft positions near tornado funnels, (2) the possible effects from silver iodide dispersed in the storm's inflow area at cloud base very near the funnel and, (3) aerial applications procedures which may be helpful in the design of future tornado seeding experiments and operational programs organized to reduce damage from these severe storms.

In the May-August period of 1970, tornado funnels were sighted during normal seeding operations on hail suppression projects near Plainview, Texas and Kericho, Kenya. Due to the excitement of the moment, little data were collected on these tornadoes other than the flight notes obtained as a routine part of normal seeding flights, (temperature, cloud base height, inflow velocity, turbulence and seeding data).

In August 1971, four other tornadoes were seeded near Plainview, Texas, while conducting weather modification operations as part of the applications hail suppression program in that area. Messrs. William Carley, Wayne Wilkinson, Phil Kowing and Barton Fisher occupied the positions of pilots and radar meteorologist during these events. A more complete set of field notes and basic data were obtained during these four seeding cases.

The events which took place during the tornado seeding of 14 May 1970 near Halfway, Texas, and of 13 August 1971 near Aiken, Texas, are described in the following sections.

2. TORNADO SEEDING ON 14 MAY 1970

On this date, the pilot of a turbocharged Twin Comanche seeding aircraft first spotted the potential tornado near Halfway, Texas, at 1700 CST by noting a circular movement of dust on the ground. Closer observation revealed a counter-clockwise rotation of reddish-brown dust approximately

1/4th mile in diameter. As the color intensity of the dust cloud increased near ground level, the pilot noted the first funnel extending from the cloud base above the rotating dust. This funnel soon reached ground level and was observed to have a blue-gray cast approximately 3/4ths of the distance from cloud base to ground. Aerial seeding began at 1702 CST in the strong inflow approximately two miles ahead of the funnel. Cloud base was noted at 7500 ft. msl with the temperature at +8C. Inflow velocities averaged 1500 ft. per min. with the aircraft set at 140 knots indicated air speed.

At 1703 the pilot of a second seeding aircraft moved into the area and began seeding in a circular path very close to, and around, the tornado funnel itself. Cloud base here was 9400 ft. msl with the temperature also at +8C. Inflow velocities averaged between 1500 and 2000 ft. per min. At this point the second seeding pilot noted the tremendous speed of the rotation and the brilliance of the reddish-brown swirling dirt on the surface. The funnel was estimated to be about 1/2 mile in diameter at ground level and nearly twice this size at cloud base elevation.

At 1707 the second seeding pilot entered the tornado funnel itself at cloud base, flying in the same direction as the rotation. Turbulence was severe and the aircraft stall warning was activated several times. At this point, the pilot widened his circular seeding path to move just beyond the main rotation. Hail approximately one inch in diameter was encountered in a small section along the west-northwest arc of the funnel. From then onward, seeding continued in a semicircular pattern away from the hailfall zone.

After some 10-12 minutes of seeding, both pilots noted an increase in diameter of the tornado at ground level and a decrease in intensity of the reddish-brown color. The diameter of the funnel at ground level continued to increase during the following two or three minute interval and this was followed by a breakdown in the rotation of the blue-gray portion of the tornado funnel extending below cloud base.

This tornado was seeded with approximately 400 grams of pyrotechnic generated silver iodide from a composition largely of magnesium, aluminum potassium nitrate, silver iodate, and an epoxy binder. Efficiency of these generators at -15C is approximately 10^{14} nuclei per gram of silver iodide.

Radar reflectivity measurements from the operational 3 cm system located some 20 miles from the tornado funnel indicated a decrease in maximum precipitation intensity within 10 minutes after seeding was initiated. During this same period, the total area covered by precipitation from this storm at any one time nearly doubled in size. No tornadoes or funnel clouds were observed from this storm system during the subsequent two-hour period of its total life.

3. TORNADO SEEDING ON 13 AUGUST 1971

At approximately 1440 on this date, a funnel cloud was observed east-southeast of Plainview near Aiken, Texas. Operating flight crews on the

hail suppression program in this area were immediately vectored to the location. On their arrival at the site, the first funnel had retreated into the parent cloud and another more active funnel had emerged about one-half mile north of the original location. At 1445, both aircraft began seeding with pyrotechnic generated silver iodide around the funnel at cloud base. Seeding continued for 15 minutes, at which time the tornado decreased in intensity and was never observed to form again from the parent cloud.

The following observational and flight notes appear significant for the total operation:

3.1 Location of Funnel Relative to Parent Cloud:

3.1.1 Eight points of the compass E-SE-S-SW-W-NW-N-NE

South of Precipitation Core 1/4th Mile

3.1.2 Relative to any inflow shelf or inflow scud

Extreme southern edge inflow shelf

3.1.3 Leading or trailing edge of parent cloud

Leading edge -- center

3.1.4 Direction and distance from any precipitation core associated with parent cloud

South 1/4th mile

3.1.5 Storm movement

1) Direction and speed of parent cloud

South-southeast 10 mph

2) Direction and speed of tornado (visual)

South 15-20 mph

3.2 Parent Cloud Information:

3.2.1 Radar tops and range

36,000 ft. above radar elevation -- range 10-15 miles

3.2.2 Cloud base (visual)

4,400 ft. msl 900-1200 ft. AGL

3.2.3 Cloud base on surrounding storm activity

5,500 ft. msl

3.2.4 Rotation within or of the parent cloud

None observed -- horizontal vortex noted

3.2.5 Does the funnel cloud extend to the upper portions of the parent cloud?

No data

3.2.6 Horizontal extent of cloud (cloud diameter)

Average size 5 x 15 miles

3.2.7 As taken from radar: Rotation, circulation, hooks, echo free vault.

Counter-clockwise rotation, cloud free paths to funnel, max reflectivity east and west of tornado, area of lower reflectivity north of tornado.

3.3 Lightning Activity:

3.3.1 Type of lightning

None observed throughout the storm life

3.3.2 Frequency of strokes

None

3.3.3 Location of electrical activity

None

3.3.4 Check for any radio distortion or static

None

3.4 Formation or Cycling Information:

3.4.1 Number of funnels observed

Total of three -- seeded only the one which reached the ground

3.4.2 Did any of the funnels cycle into the main cloud and return?

Funnel #3 may have been the dying stage of the seeded tornado

3.4.3 Total time the tornado or funnel cloud was visible.

1438-1503 CDT: Total - 25 minutes

3.4.4 Was the parent cloud seeded -- start and stop times

Seed 1445 until 1500

3.4.5 How long did the funnel last after seeding began?

Main tornado dissipated 15 minutes after seeding started.

3.4.6 How many grams of seeding material used?

315 grams AgI

3.5 Rotation of Tornado:

3.5.1 Type of rotation

Counter-clockwise

3.5.2 Estimated speed of rotation (rpm)

Estimate 500 rpm at ground level -- 100 rpm at cloud base.

3.5.3 Is the rotational speed constant throughout the vertical extent of the funnel, or does it vary from top to bottom?

Always seems to be greater rotational speed near ground.

3.5.4 Any significant patterns in the debris which may be a clue to the damage potential of tornado?

Debris thrown further on the south side (confirmed by photo data).

3.5.5 Is a sheer point evident where rotating winds of the funnel meet the prevailing winds of the storm cloud?

No

3.5.6 Any specific observations on the blown-up debris or funnel core?

Funnel core is often hollow. Blown-up debris at ground level is separated by clear air space between this debris and outside of funnel wall.

3.5.7 Erratic movement of tornado funnel.

Tornado moves faster over fallow ground than over crop land or obstructions -- this funnel moving south and whipping east to west.

3.6 Physical Characteristics of Funnel Cloud:

3.6.1 Length, diameter, color, ability to see through

1,000 ft. long, 500 ft. diameter at ground level, translucent gray

3.6.2 Observe area where funnel joins parent cloud, solid or open space, diameter comparison.

No breaks in tornado funnel, slightly larger diameter at cloud base.

3.6.3 Any darker inner core observed and direction of rotation.

Yes, same rotation as main funnel

3.6.4 Any portion of funnel filling with water when passing over lakes, rivers or ponds.

No data

3.6.5 Was the funnel hollow at any point?

Yes

3.7 Airborne checks:

3.7.1 Altimeter, IVSI and other static instruments as a check against any large or rapid pressure changes.

Static instrument remained fixed -- no pressure change.

3.7.2 Record levels of turbulence in and around funnel area.

Moderate to occasionally severe turbulence. Most severe turbulence located just ahead of tornado funnel about 1/8th mile.

3.7.3 Check vertical velocities, both up and down.

1500-2500 ft. per min. up -- 1500 ft. per minute down.

3.7.4 Any temperature change from surrounding areas or levels next to the funnel.

Nothing significant.

3.7.5 Was the funnel cloud penetrated?

No

3.7.6 Could it have been penetrated?

Both pilots reported "no" because of speed of rotation and low cloud base.

3.7.7 Where would you have elected to penetrate?

Along the southeast arc gradually entering the funnel flying in same direction as rotation.

4. SYNOPTIC WEATHER SUMMARY -- 13 AUGUST 1971

The synoptic weather pattern in the West Texas area during the period 11-14 August 1971 was dominated by a large high pressure area centered in the east-central United States. This almost stationary system provided a very moist and unstable southeasterly surface flow throughout the state. Scattered air mass thunderstorms occurred almost every day during this period from the South Plains through Central Texas.

Above normal precipitation in the Plainview area was accompanied by temperatures which averaged 5-6C below normal. During the first two weeks of August the area had received 5-7 inches of rain when the August normal is less than two inches.

On August 11th a week tropical disturbance, "Katrina," moved into the western coast of Mexico. At the 700 mb level, an inverted trough and associated moist tongue extended northeastward into eastern New Mexico. A week closed low just south of El Paso was noted on the 500 mb chart. The moist layer was deep at both Midland and Amarillo extending from the surface to 500 mb. On August 12th, cooler and drier air had moved into the Midland and Amarillo area and the week low at 700 mb still existed in eastern New Mexico. By now, the 500 mb low had moved to the vicinity of Lubbock, Texas.

On Friday, August 13th, the closed low which was located in eastern New Mexico at the 700 mb level had moved to the vicinity of Amarillo. The closed low at the 500 mb level was no longer apparent but the associated trough could be located between Amarillo and Midland. For the Plainview area, no severe weather was forecast on the National Weather network.

The severe thunderstorms in the Plainview area which spawned the tornado on August 13th, were probably triggered as the convergence area moved northeast with the troughs at the 700 and 500 mb levels. A depiction of the operational 3cm radar scope located at Plainview is shown in Figure 1. Time of depiction coincides with the transition between funnel cloud and actual tornado touchdown.

5. CONCLUDING REMARKS

Needless to say, there has been some concern on the part of all operating personnel with respect to the possibility of increasing tornado

intensity by application of silver iodide ice nuclei. The decision to move ahead with these seeding experiments has been based, in part, on rather extensive experiments of seeding several thousand severe storms for purposes of reducing hail damage. One might conclude, inasmuch as programs are already designed to seed potential tornado producers, it is permissible to move ahead with the application if a tornado is observed. In any case, the results from many seeding events have indicated that no tornadoes have ever developed from any severe storm cells which have been seeded for at least 20 minutes, and where not less than 200 grams of silver iodide have been applied in this same time period.

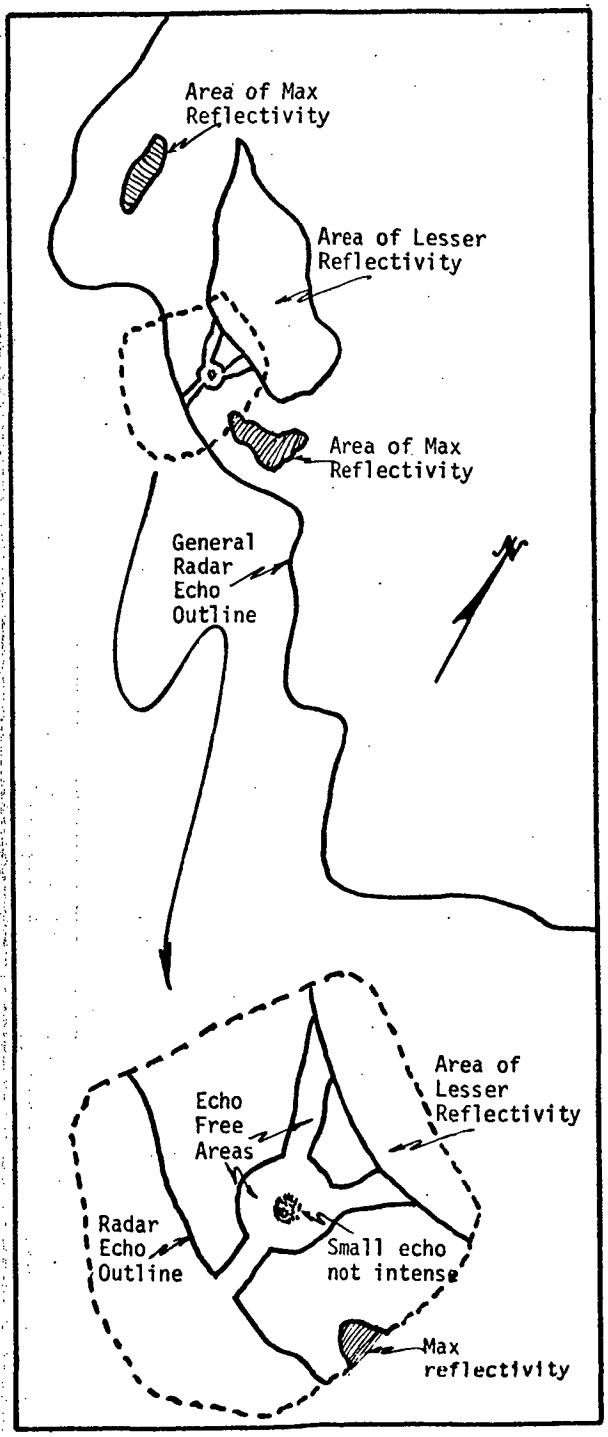
Considerable thought has also been given to the movement of aircraft in and around the tornado funnel as the seeding events progress. In all six cases so far treated, the aircraft has moved into seeding position from a location ahead of the funnel cloud or tornado and moved around the funnel in the direction of rotation. While the turbulence has been occasionally recorded as severe, there has been no experience of forces strong enough to produce serious aircraft damage when flying at cloud base. The concentration of forces at ground level appear much greater than those experienced at the higher elevations.

The important point in these experiments to date is not that the tornado intensity decreased following seeding but rather that the tornado intensities <u>have not increased</u> following the seeding application. It seems additionally important that the maximum radar reflectivities have decreased following application of material and the overall areas of precipitation have increased significantly.

After examining the rather limited data acquired from these six tornado seeding cases, it appears logical to now cautiously move ahead with further tornado seeding experiments which have improvements in design considerations and operational criteria.

FIGURE 1.

3.2 cm Radar Observation
of Tornado Area at 1455
13 Aug. 1971



MODIFICATION OF THE HYDRODYNAMIC MASS

BY ENTRAINMENT

by

Ira Kohlberg*

1.0 INTRODUCTION

Darwin[1] seems to have been the first to clearly point out that when a solid body moves through an imcompressible fluid, a net drift of fluid is induced, which can be interpreted as fluid momentum. If $\vec{v}$ is the velocity of the solid body, and V_o its volume, then Darwin's result may be summarized by the equation for the total momentum, $\vec{P}$, of the combined body-plus-fluid system: we have

$$\vec{P} = m\vec{v} + \rho\ (\alpha V_o)\ \vec{V} = M\vec{v} \tag{1.1}$$

where m is the body's mass, ρ the fluid density, and α is constant which depends on the shape of the solid body (e.g. $\alpha = \frac{1}{2}$ in the case of a sphere). As observed, $\vec{P}$ is composed of the body momentum $m\vec{v}$ plus the fluid momentum $\rho\ (\alpha V_o)\vec{v}$. The volume αV_o is what Darwin calls the drift-volume, while $\rho\alpha V_o$ is the hydrodynamic mass, that is, the mass of fluid to be added to that of the solid in calculating its kinetic energy. Thus, a body of mass m behaves like one of mass $M = m + \rho\ (\alpha V_o)$ when moving through a nonviscous, incompressible fluid of constant density ρ.

In this note we shall investigate modifications to the foregoing results in the case where the solid body expands and were there is a mixing between the "solid" body and the fluid. The necessity for dealing with the hydrodynamic mass arises from the following circumstances.

Regardless of the interactions between a body and the fluid through which it passes it is always possible to write down the equations

$$\frac{d\vec{P}_b}{dt} = \vec{F}_{bf} + \vec{F}_{be} \tag{1.2}$$

$$\frac{d\vec{P}_f}{dt} = \vec{F}_{fb} + \vec{F}_{fe} \tag{1.3}$$

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where $\vec{P}_b$ and $\vec{P}_f$ are the body and fluid momenta, $\vec{F}_{bf}$ is the force excited on the body by the fluid, ($\vec{F}_{fb} = -\vec{F}_{bf}$) and $\vec{F}_{be}$ and $\vec{F}_{fe}$ are the external forces on the body and fluid respectively. The principal obstacle concerned with the use of Eqs. (1.2) and (1.3) is the difficulty of formulating $\vec{F}_{bf}$, particularly when there are deformations in the body's shape coupled with an interchange of mass. Because it is usually possible to relate $\vec{P}_f$ to the properties of the body in question, it is much easier, if not absolutely necessary, to solve a given problem by the addition of Eqs. (1.2) and (1.3). We then have

$$\frac{d\vec{P}}{dt} = \vec{F}_e, \tag{1.4}$$

where $\vec{P} = \vec{P}_b + \vec{P}_f$ and $\vec{F}_e = \vec{F}_{be} + \vec{F}_{fe}$ is the entire external force on the system.

As a matter of interest, we may also ask at this point, where the drag force enters into the picture since it is certainly not an external force when the body-plus-fluid system is viewed as a whole. For instance, one finds experimentally that the instantaneous velocity $\vec{U}(t)$ of a spherical body of radius R moving through a fluid of density ρ decays according to the equation

$$(m + \tfrac{2\pi}{3}\rho R^3)\,\frac{d\vec{U}}{dt} = -\vec{F}_D\,(\vec{U},R) \tag{1.5}$$

where the drag force, $\vec{F}_D$, is a function of $\vec{U}$ and R. Since the virtual momentum $\rho\,\frac{2\pi}{3}\,R^3\vec{U}$ has already been incorporated into the picture, Eq. (1.5) seems to violate the conservation of momentum. The answer to this paradox is that $2\pi\rho R^3/3$ is not the entire fluid momentum. There is another non-equilibrium part denoted by $\vec{P}'$ which is due to turbulence. The rate of change of this component of momentum is given by

$$\frac{d\vec{P}'}{dt} = \vec{F}_D\,(\vec{U},\,R) \tag{1.6}$$

so that the entire momentum

$$\vec{P} = m\vec{U} + \tfrac{2\pi}{3}\rho R^3\vec{U} + P' \tag{1.7}$$

is conserved.

Thus, the hydrodynamic mass is useful in describing the kinetics of the non-turbulent part of body motion in a fluid.

2.0 ANALYSIS OF FLUID MOMENTUM

The momentum of the fluid, $\vec{P}_f$, is given by the expression

$$\vec{P}_f = \rho \int \vec{v}(\vec{r}) \; dV_f \tag{2.1}$$

where $\vec{v}(\vec{r})$ is the fluid velocity and the integration extends over the entire space occupied by the fluid ($\int dV_f$). For a sphere moving with instaneous velocity $\vec{U}$ (in the z direction) through the fluid the integration in Eq. (2.1) can be performed under a wide variety of irrotational flow patterns.

In the reference frame of the sphere the fluid velocity is derivable from a potential function ϕ by the equation

$$\vec{v} = - \nabla \phi \tag{2.2}$$

where

$$\phi = Ur \cos\theta + \psi, \tag{2.3}$$

$$\psi = \sum_{n=0}^{\infty} B_n \, r^{-(n+1)} \, P_n(\mu), \tag{2.4}$$

$P_n(\mu) = n^{th}$ Legendre polynomial, and $\mu = \cos\theta$. Figure 1 shows the pertinent geometric details.

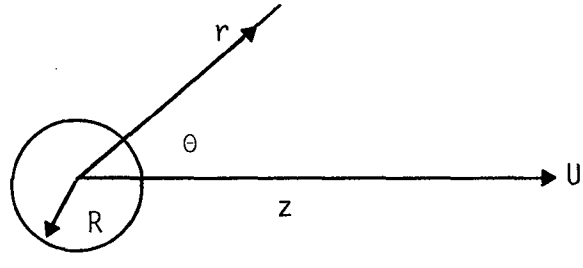

FIG. 1 MOVING SPHERE IN FLUID

In this reference frame the fluid at infinity moves with velocity - U in the z direction. It also follows that in the reference frame in which the fluid at infinity is at rest the fluid velocity is given by

$$\vec{v} = - \nabla \psi, \tag{2.5}$$

and in particular the z component of velocity, v_z, is given by

$$v_z = - \mu \frac{\partial \psi}{\partial r} - \frac{(1-\mu^2)}{r} \frac{\partial \psi}{\partial \mu} \tag{2.6}$$

Using the relationship (cf. reference 2)

$$(1-\mu^2)\frac{\partial P_n}{\partial \mu} = (n+1)\left[\mu P_n - P_{n+1}\right] \tag{2.7}$$

in the term by term differentiation of Eq. (2.4) as required by Eq. (2.2) gives the following expression for the z component of fluid momentum (Eq. (2.1)

$$P_{f,z} = \rho \int \sum_{n=0}^{\infty} B_n r^{-(n+2)} (n+1) P_{n+1} dV_f \tag{2.8}$$

where

$$dV_f = 2\pi \sin\theta d\theta \; r^2 dr \tag{2.9}$$

we have:

$$P_{f,z} = 2\pi\rho \sum_{n=0}^{\infty} B_n (n+1) \int_{-1}^{+1} P_{n+1}(\mu) d\mu \int_R^{\infty} r^{-n} dr \tag{2.10}$$

For $n \geq$ the integrations are absolutely convergent; and combining this with the orthogonality of the P_n's, that is

$$\int_{-1}^{+1} P_n P_m \, d\mu = \delta_{mn} \left(\frac{2}{2n+1}\right)$$

renders all terms in Eq. (2.10) zero for $n \geq 2$. On the other hand the $n = 0$ term vanishes identically from symmetry. Thus, the only contribution to $P_{f,z}$ comes from the $n = 1$ term; the double integral

$$P_{f,z} = 4\pi \rho B_1 \int_{-1}^{+1} P_2 (\mu) \, d\mu \int_R^{\infty} \frac{dr}{r} \tag{2.11}$$

is unfortunately not absolutely convergent and can attain quite different values according to which integration is done first. This has been recognized earlier by Darwin who has demonstrated on physical grounds that the

$$\int v_z \, dV_f$$

should be performed in a coordinate system in which the integration in the direction of the flow is to be performed first, followed by the integration over the transverse coordinates. This will avoid the ambiguity associated with the evaluation of Eq. (2.11).

Consequently the expression for $P_{f,z}$ becomes

$$P_{f,z} = 2\rho B_1 \int (P_2 (\mu)\ r^{-3})\ dV_f \qquad (2.12)$$

where the fluid volume is the solid cylinder of radius R_o and height 2L surrounding the sphere of radius R, (cf. Fig. 2). By treating the cylinder as a solid of revolution we have

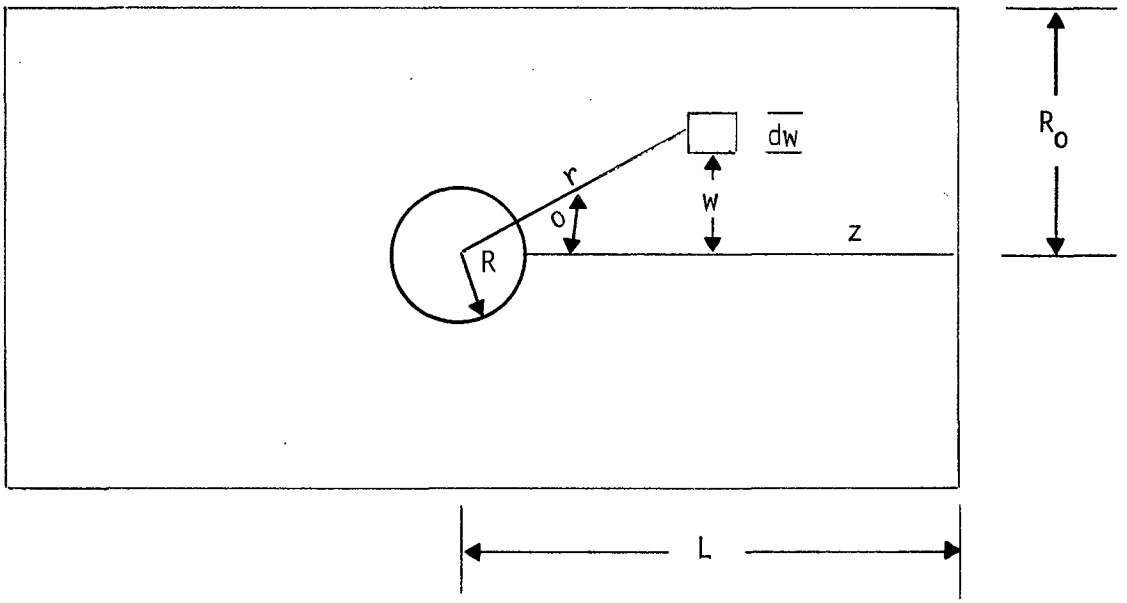

FIGURE 2 VOLUME FOR INTEGRATION OF $P_2\ (\mu)\ r^{-3}$

$$dV_f = 2\pi\ w dw\cdot dz \qquad (2.13)$$

and

$$P_2\ (\mu) = \frac{1}{2}\ (3\mu^2-1)\ = \frac{1}{2}\left(\frac{3z^2}{z^2 + w^2}\ -1\right) \qquad (2.14)$$

with the condition

$$z^2 + w^2\ \geq R^2 \qquad (2.15)$$

Inserting Eqs. (2.13) and (2.14) into Eq. (2.12) and performing the integration from $-L \leq z \leq + L$ first (letting $L \to \infty$) followed by the integration of w from 0 to $R_o \to \infty$ gives the result for P_z (the details are too extensive to reproduce here).

$$P_{f,z} = \frac{4\pi\rho}{3} B_1 \tag{2.16}$$

The foregoing result, namely that of specifically relating $P_{f,z}$ to B_1, does not seem to have been previously stated because other methods, which circumvent the explicit calculation of $P_{f,z}$ are available (cf. Landau and Lifshitz, reference 3) for relating $P_{f,z}$ to U and R in the case of a solid, constant radius, and nonentraining sphere.

The explicit dependence of the fluid momentum $P_{f,z}$ on the properties of the flow field is found from the boundary conditions at the surface of the sphere. This is discussed in the next section.

3.0 POSSIBLE EXPRESSIONS FOR $P_{f,z}$

The relative radial component of velocity at the surface of the sphere, $V_R(\mu)$, is given by

$$V_R(\mu) = -UP_1 + \sum_{n=0}^{\infty} B_n (n+1) R^{-(n+2)} P_n(\mu) \tag{3.1}$$

and hence specification of $V_R(\mu)$ determines all the coefficients for the flow field. Multiplying Eq. (3.1) by $P_k(\mu)$ and then integrating over μ gives

$$\left(\frac{2k+1}{2}\right)\gamma_k = -U\delta_{1k} + (k+1) R^{-(k+2)} B_k \tag{3.2a.}$$

or alternately,

$$B_k = \left(\frac{R^{(k+2)}U}{k+1}\right)\delta_{1k} + \frac{2k+1}{2(k+1)} R^{(k+2)}\gamma_k \tag{3.2b.}$$

where

$$\gamma_k = \int_{-1}^{+1} V_R(\mu) P_k(\mu)\, d\mu \tag{3.3}$$

In the case of a non-entraining sphere $V_r(\mu) = 0$ and we have $\gamma_k = 0$ (all k) so that

$$B_1 = \frac{UR^3}{2} \tag{3.4}$$

$$B_k = 0 \quad (k \neq 1) \tag{3.5}$$

and

$$P_{f,z} = \left(\frac{1}{2}\ \frac{4\pi}{3}\ R^3\right)\rho U \tag{3.6}$$

Eq. (3.6) is the well-known result connecting the fluid momentum to U for a constant radius non-entraining sphere.

However, the present formalism permits modifications to Eq. (3.6) through the alteration of B_1 by entrainment. In order to illustrate the relative effects which may be anticipated from entrainment, let us consider the arbitrary case where

$$V_R(\mu) = -\xi\mu : 0 \leq \mu \leq 1 \quad (0 \leq \theta \leq \pi/2)$$

$$V_R(\mu) = 0 \quad : -1 \leq \mu \leq 0 \quad (\pi/2 < \theta < \pi) \tag{3.7}$$

where ξ is the relative z component of velocity at the surface of the sphere. The mass entrainment, $\dot{m}$, due to $V_R(\mu)$ is

$$\dot{m} = -2\pi R^2 \rho \int_{-1}^{+1} V_R(\mu)\, d\mu = -2\pi R^2 \rho \gamma = \pi R^2 \rho \xi \tag{3.8}$$

Using Eq. (3.2b) in Eq. (2.16) then gives

$$P_{f,z} = \frac{1}{2}\left(\frac{4\pi}{3} R^3\right)\rho U - \frac{\pi \rho R^3 \xi}{3} \tag{3.9a}$$

$$= \frac{1}{2}\left(\frac{4\pi}{3} R^3\right)\rho U - \frac{\dot{m} R}{3} \tag{3.9b}$$

Notice, that in this entrainment model the fluid in front of the cloud is moving slower than the cloud by the amount ξ so that the absolute velocity of the fluid in this region is

$$V_f = U - \xi \tag{3.10}$$

All physical reasoning seems to suggest that at least for rising clouds or bubbles in the atmosphere we should have

$$0 \leq V_f \leq U \tag{3.11}$$

so that ξ should for all time be restricted to the range

$$0 \leq \xi(t) \leq U(t) \tag{3.12}$$

The complete solution to a given problem, of course, hinges on relating ξ or $\dot{m}$ to the other variables in the system. By way of illustration let us assume that ξ is given by:

$$\xi = kU, \tag{3.13}$$

with k is restricted to the range*

$$0 \leq k \leq 1 \tag{3.14}$$

*Physically, this corresponds to the case in which the induced fluid velocity is proportional to the instanteous value of the entraining sphere velocity. We are not making an effort at this point to render a detailed physical justification for the mathematical model since the main emphasis in this study is to demonstrate the possible effect of entrainment on the hydrodynamic mass.

The fluid momentum then becomes

$$P_{f,z} = \rho(\alpha V_o) U \tag{3.15}$$

where

$$\alpha = \frac{1}{2} - \frac{k}{4} \tag{3.16}$$

The foregoing equation demonstrates the important result that the effective fluid momentum may be reduced by as much as 50% in the case where k=1. It is also interesting to note that the assumed behaviour indicated by Eq. (3.13) is also consistent with the experimentally deduced limitations on the entrainment rate in the case of nuclear clould rise models[4] as can be seen from the following argument. $\dot{m}$ must be less than or equal to the total entrainment rate

$$\dot{m}_T = \rho 4\pi R^2 \dot{R} \tag{3.17}$$

(derived on the basis of constant pressure mixing), which using Eqs. (3.8) and (3.12) implies

$$k \leq 4\dot{R}/U \tag{3.18}$$

For the early stages of entrainment-controlled cloud rise we have the experimental relationship[4]

$$\dot{R} = \gamma U \tag{3.19}$$

where γ is a constant that ranges from 0.25 to 0.50. On the other hand, for later times dR/dt approaches a constant value while U diminishes. Thus, a typical plot of $4\dot{R}/U$ versus time would look like the graph shown in Fig. 3.

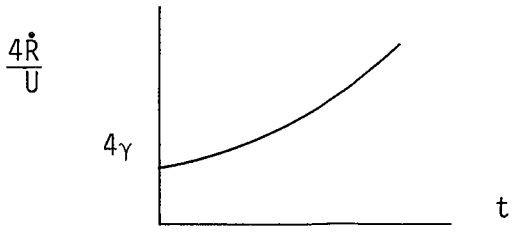

FIGURE 3 PLOT OF $4\dot{R}/U$

Since γ is greater than 0.25 we have

$$\left(\frac{4\dot{R}}{U}\right)_{min} = 4\gamma > 1, \tag{3.20}$$

which from Eq. (3.18) shows that the condition

$$0 \leq k \leq 1 \tag{3.21}$$

is consistent with experimental observations.

From the foregoing example it is clear that other models of entrainment would necessarily yield correspondingly different values for the effective mass,

$$M = m + \rho \alpha V_0 \tag{3.22}$$

due to the dependence of α on the entrainment mechanism.

In summary, then, we have been able to show in general and in a formal mathematical way how entrainment can affect the fluid momentum. For the specific entrainment model used in this investigation we have been able to interpret the pertinent results in terms of a modified drift volume (with respect to the non-entrainment case). Other entrainment models will yield correspondingly different relationships between the fluid momentum and the properties of the body.

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THE SPATIAL DISTRIBUTION OF CLOUD SEEDING NUCLEI FROM GROUND-BASED GENERATORS

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ABSTRACT

The results of both the computed and measured spatial distribution of AgI nuclei released from a network of ground-based generators are presented. Numerical solutions of the Gaussian plume diffusion model were obtained for various atmospheric conditions, characterized by suitable dispersion coefficients. The computed values of such parameters as plume width, maximum nuclei concentrations and their variation with height is compared to those obtained by direct measurements, carried out by suitably instrumented aircraft. Under conditions of slightly unstable atmosphere the agreement between the computed and the measured values is quite reasonable.

One of the important implications is that for an efficient area seeding in a flat terrain an increased number of generators having higher nuclei outputs is required.

INTRODUCTION

Cloud seeding experiments directed to stimulate precipitation are designed on the basis of some assumptions, of which the following are of dominant importance and are relevant to this work:

a) The introduction of artificial ice-forming nuclei, in suitable clouds, in sufficient concentrations will result in an overall increase of precipitation;

b) The seeding material released either from the ground or from air-borne generators diffuses in the atmosphere in such a manner, that it reaches the clouds in these sufficient concentrations.

In cloud seeding experiments that are aimed at affecting the total precipitation of an area rather than that of a single cloud, an estimate of the fraction of the total area affected is quite necessary. Further-

more an estimate of plume dimensions is also required in the design of area seeding experiments where the control area is adjacent to the target area. Care should be taken not to contaminate the control area while seeding the target area.

Ice nuclei measurements, for the purpose of tracking the nuclei output of AgI generators, were made possible, with certain restrictions, through the use of continuous nuclei counters such as the NCAR acoustical counter, Langer et al. (1965). This report is an attempt to give an estimate of the spatial distribution of cloud seeding nuclei emitted from ground based generators on the basis of computations carried out with known models of atmospheric diffusion and on the basis of direct measurements in the atmosphere.

THEORETICAL BACKGROUND

The problem to be considered below is that of describing, by means of numerically modified mathematical-physical models, the effects of the lower atmosphere in dispersing and diluting the nuclei outputs of ground based AgI generators. The solution to this problem can be approximated by the use of models describing the characteristics of plumes emitted by continuous point sources.

An extensive survey of the problems involved in such studies is given in "Meteorology and Atomic Energy, 1968".

The Gaussian plume diffusion (G.P.D.) model assuming a normal distribution of the diffusing material released from a continuous point source was widely and quite successfully used. Strictly speaking this model applies only in the limit of large diffusion time and for homogeneous and stationary atmospheric conditions. The model can be described by:

$$\chi(x,y,z) = \frac{Q}{2\pi\bar{U}\sigma_y\sigma_z} \exp\left(-\frac{y2}{2\sigma_y^2}\right) \exp - \frac{(z+h)^2}{2\sigma_z^2} + \exp\frac{(z-h)^2}{2\sigma_z^2} \quad (1)$$

where $\chi(x,y,z)$ is the spatial concentration of the released material, Q is the rate of its release, $\bar{U}$ is the average horizontal wind speed, σ_y and σ_z are the horizontal and vertical dispersion coefficients respectively, h is the effective release height and x,y,z are the downwind, crosswind and vertical coordinates respectively.

The use of this model is restricted to the customary limitations of flat terrain and invariance of wind with height, the latter being somewhat unrealistic for our conditions.

The effective release h can be computed by considering the buoyancy and the vertical momentum of the emitted material by Holland's formula, Islitzer & Slade (1968):

$$\Delta h = 1.5d \frac{W}{\overline{U}} + 4.0 \times 10^{-5} Q_H \qquad (2)$$

where Δh is the plume rise, W is the velocity of the emitted gas, d is the chimney's diameter and Q_H is the rate of heat emission of a continuous source.

Another model that has been considered is the one derived by Sutton (1953). It can be described for a ground continuous point source, by

$$\chi(x,y,z) = \frac{2Q}{\pi \overline{U} \sigma_y \sigma_z X^{2-n}} \exp \left[-X^{n-2} \left(\frac{y^2}{C_y^2} + \frac{Z^2}{C_z^2} \right) \right] \qquad (3)$$

where C_y and C_z are the so-called virtual diffusion coefficients and n is a parameter which characterizes the atmospheric static stability and can be determined, assuming a power law wind profile from:

$$\frac{\overline{U}_1}{\overline{U}} = \frac{Z_1}{Z_2}^{\frac{n}{2-n}} \qquad (4)$$

where $\overline{U}_i$ is the mean wind speed at altitude Z_i.

In both models the crucial problem is that of the proper choice of the representative dispersion coefficients. At present, exact analytical expressions of these coefficients do not exist. However, attempts are usually made to determine their values empirically. Thus, they cannot be of a general form but depend rather critically on the specific conditions of static stability under which they were made.

In the Gaussian plume diffusion, (G.P.D.) model the σ_y and σ_z parameters, are dependent on atmospheric static stability and on the distance from the source while C_y, C_z and n used in Sutton's diffusion model, are assumed to be constant with distance from the source but are again dependent on stability. In both models the large scale stability effects are neglected.

Good agreement was obtained, by many workers between the actually measured values and those computed with the Gaussian Plume Diffusion model utilizing the dispersion coefficients, empirically derived by Pasquill: Gifford, (1968). Alternatively, the σ_y, σ_z values can be derived from the vertical wind profile by assuming that they have a power law variation with distance from the source.

$$\sigma y = \alpha x^p \qquad (5)$$

$$\sigma z = \beta x^q \qquad (6)$$

where α, β, p and q are constants dependent on the stability of the lower atmosphere.

Since the field measurements were of interest for conditions with a good likelihood for precipitation, i.e. in this part of the world with some degree of instability, special attention is given to computations for conditions defined as "slightly unstable". For the sake of comparison, other computations for different stability conditions are also given.

Table 1 gives the details of the various values of the dispersion coefficients for these types of weather. The representative values, for conditions defined as slightly unstable, for the Sutton Diffusion Model are: $C = 0.54$, $C_z = 0.32$, $n = 0.48$, this being suggested and tested by the Brookhaven National Laboratory, Islitzer and Slade (1968).

Stability Criteria		Distance downwind from the Generators (km)							Reference
		1	2	5	10	20	50		
1) Pasquill	σ_y	0.11	0.2	0.45	0.85	1.5	2.2	-	Pasquill
a) Slightly Unstable	σ_z	0.07	0.12	0.2	0.45	0.6	1.5		(1968)
b) Unstable	σ_y	0.14	0.25	0.55	0.99	1.8	3.97	$\sigma_y = 0.68x^{0.86}$	
	σ_z	0.13	0.23	0.5	0.92	1.66	3.66	$\sigma_z = 0.32x^{0.86}$	M. Smith
c) Very Unstable	σ_y	1.22	0.41	0.94	1.78	3.31	7.68	$\sigma_y = 0.4x^{0.91}$	(1968)
	σ_z	0.22	0.41	0.94	1.78	3.31	7.68	$\sigma_z = 0.4x^{0.91}$	
d) Neutral	σ_y	0.07	0.12	0.25	0.43	0.73	1.50	$\sigma_y = 0.32x^{0.8}$	
	σ_z	0.05	0.08	0.17	0.29	0.5	1.05	$\sigma_z = 0.22x^{0.78}$	
2) Tadmor	σ_y	0.18	0.39	0.89	1.67	3.13	7.14		Tadmor & Gur
	σ_z	0.7	0.94	1.81	2.99	4.9	9.45		(1969)

Table 1. The dispersion coefficients as a function of distance for the various models and stability criteria.

NUMERICAL COMPUTATIONS

The computations were done for an existing network of 13 groundbased generations, see attached map, fig. 1. Since one of the basic requirements of the model is a flat terrain, we have confined the measurements for comparisons with the computed values to a region which is quasi flat and is also about 30 km. downwind from the generators.

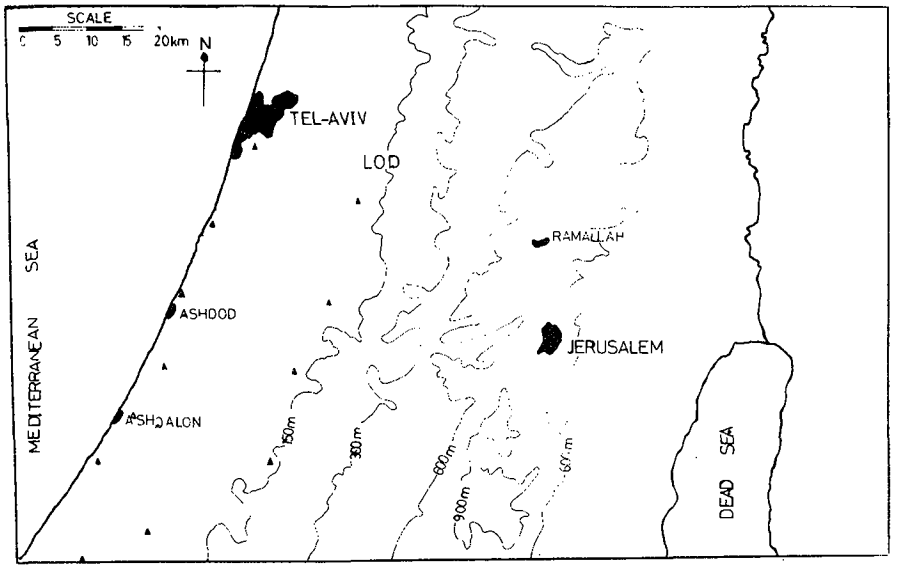

Fig 1: Map of the area and the distribution of ground generators ( ).

The total area for the computation is 80 x 80 km. The grid size of the network under consideration was taken to be 1 km. The computer (CDC 6400) was programmed to give constant altitude maps, demonstrating the distribution of AgI nuclei concentrations at -15^{0}C.

Figs. 2,3,4,5 display these results for heights of 400, 600, 800 and 1000 meters respectively. The Pasquill values, for conditions defined as "slightly unstable" were applied in these solutions. Figs. 7,8,9 demonstrate the effects of the various stability criteria on the solutions obtained with the same G.P.D. model. The results obtained with Sutton's model, with the above mentioned coefficients, as well as those obtained with the G.P.D. model using Tadmor & Gur's (1969) for conditions defined as slightly unstable, are given in figs. 6 and 10, respectively. All the computations were done assuming an output of 5.10^{13} nuclei per gram of AgI, active at -15^{0}C. The burning rate being 12 $g.hr^{-1}$.

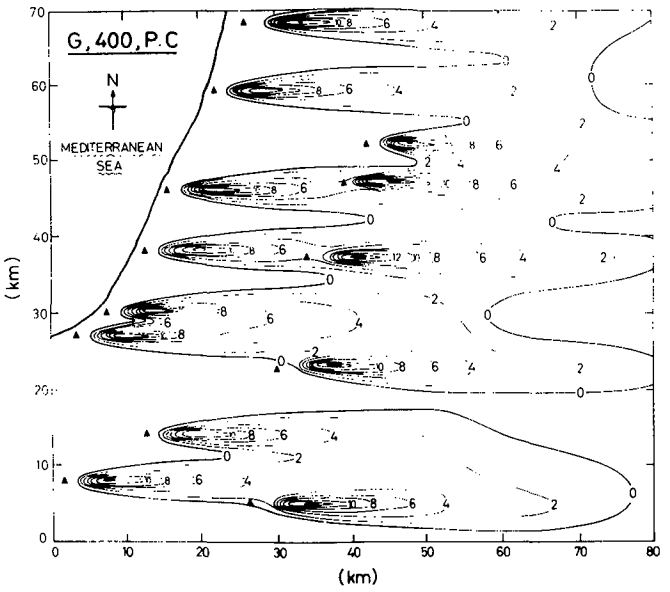

Fig. 2. The distribution of AgI nuclei at 400m a.s.1. as computed by the G.P.D. model, assuming slightly unstable conditions.

Table 2 summarizes these results and the following conclusions can be drawn:

1) Maximum plume width decreases for conditions defined as slightly unstable by a factor of 2 for a change of height, from 400 to 1000.

2) The distance where the plume attains its maximum width, in any given altitude, is independent of height for slightly unstable conditions and is of the order of 30 km.

3) Maximum concentrations, emitted by one source and for the same conditions, undergo a change of one order of magnitude for a variation of height from 400 m to 1000 m.

Downwind length of the indicated iso-concentration lines				Distance of max. concentration	Max. concentration for one source	Distance of max. plume width	Max. plume width			
20	10	4	0	(km)	N/lit.	(km)	(km)	Stability criteria	Height above ground (m)	The model
2	7	22	50	7	20	32	8	slightly unstable	400	Gauss Pasquill C
--	--	15	40	11	6	30	7	slightly unstable	600	Gauss Pasquill C
--	--	--	37	10	2	30	6	slightly unstable	800	Gauss Pasquill C
2	--	--	35	15	2	30	4	slightly unstable	1000	Gauss Pasquill C
--	30	--	60	12	10	27	3	slightly unstable	400	Sutton n=0.4 =0.54 =0.32
--	2	4	10	3	10	6	4	slightly unstable	400	Gauss (Tadmor)
6.4	15	--	25	5	20	10	3.7	unstable	400	Gauss (M. Smith)
1	3	4	5	3	10	3	2	very unstable	400	Gauss (M. Smith)
--	20	--	38	6	10	10	2.5	neutral	400	Gauss (M. Smith)

Table 2. Summary of results obtained by numerical computations.

4) The distance, from the source, for which the maximum concentration in any given altitude is attained, increases with altitude.

5) The maximum width of the plume (for a given concentration) is obtained for intermediate conditions, i.e.: slightly unstable. For either neutral or very unstable conditions this width is narrower. The same applies to the distance for which the maximum width is obtained.

6) The total area affected (by a given concentration or higher) is again the largest for conditions defined as slightly unstable. An example of this can be seen in fig. 2, for the level of 400 meters above sea level.

7) The above conclusions apply only to the G.P.D. model. The nuclei distributions under slightly unstable conditions for the Sutton D. model and for the G.P.D. model with diffusion coefficients derived by Tadmor and Gur, 1969, are also displayed and will also be compared to the actually measured distributions.

8) These computations, with the G.P.D. model and others, suggest that as far as relative distributions are concerned, best results (maximum concentration and plume widths) are obtained under conditions defined as slightly unstable.

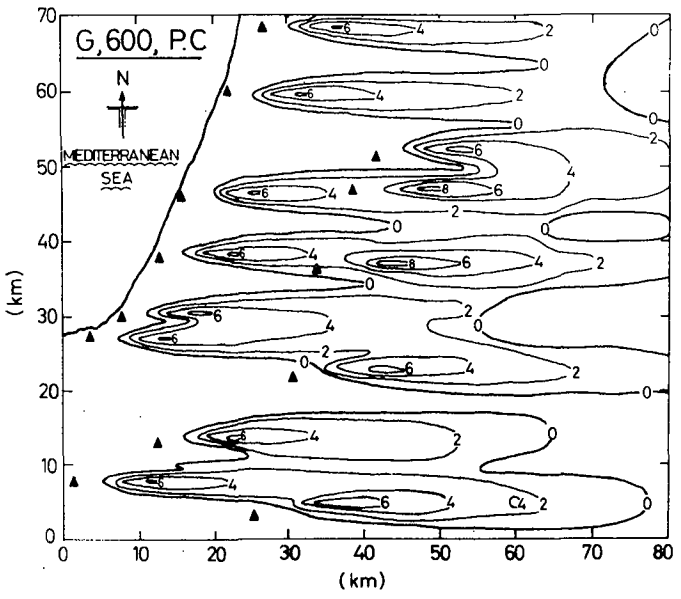

Fig. 3

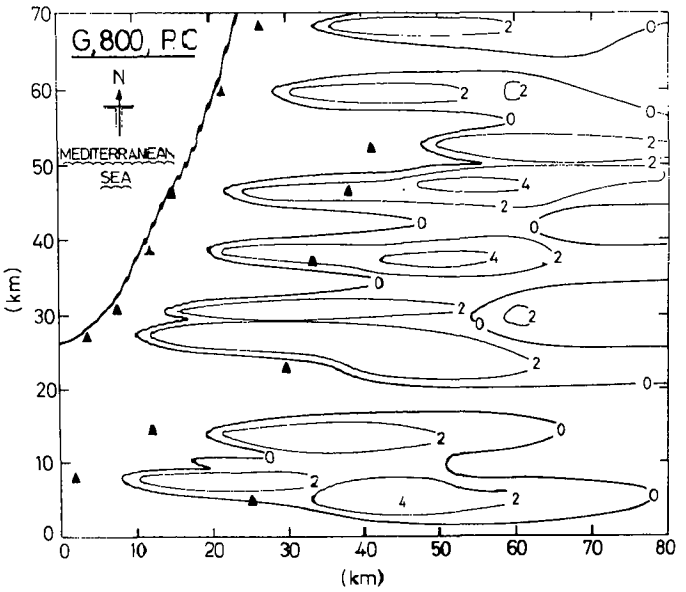

Fig. 4

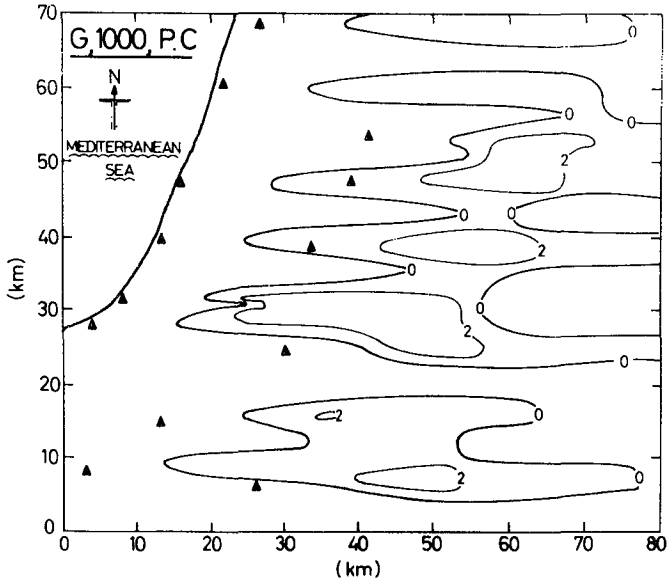

Fig. 5

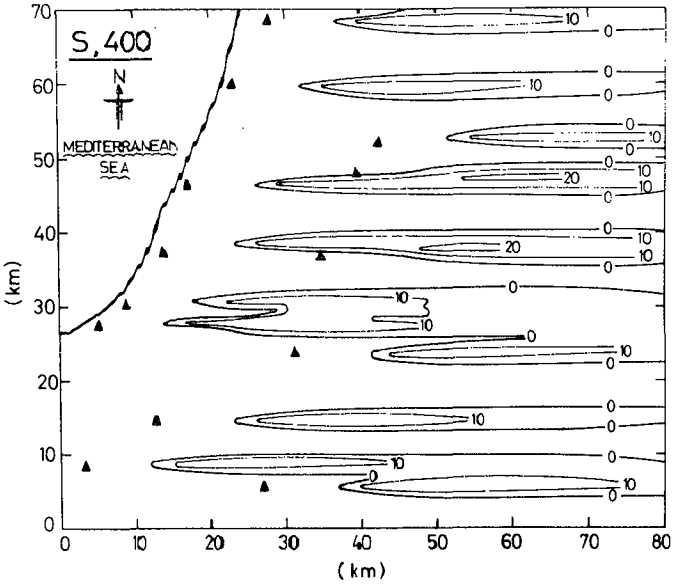

Fig. 6

The distribution of AgI nuclei as computed by the G.P.D. model under conditions defined as "slightly unstable." Figs. 3,4,5 give these results for the altitudes 600, 800, 1000m a.s.l. respectively. Fig. 6 displays the solution for 400m a.s.l. obtained with Sutton's model.

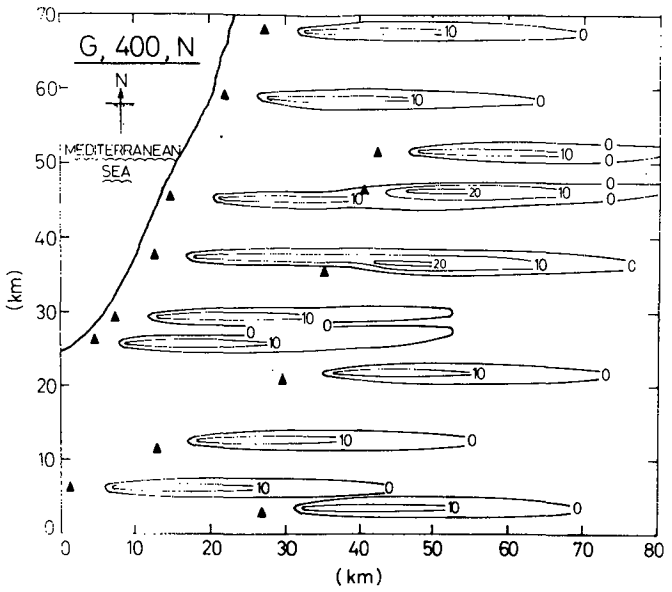

Fig. 7 (neutral)

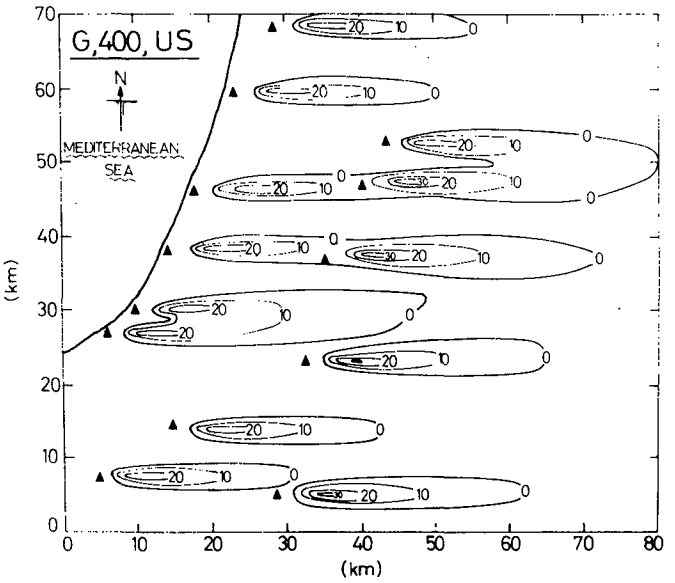

Fig. 8 (unstable)

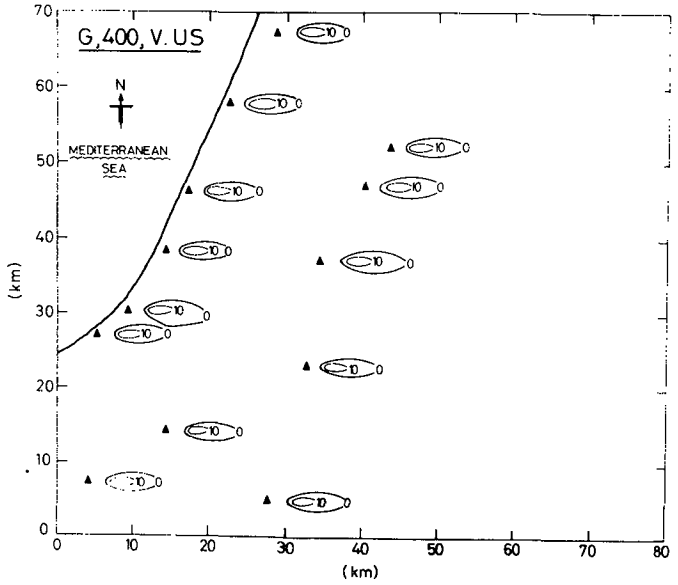

Fig. 9 (very unstable)

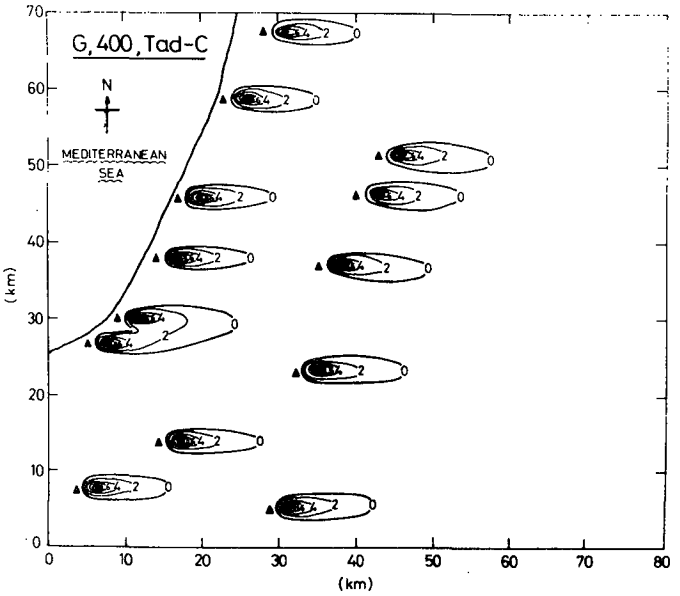

Fig. 10

The dependence of AgI nuclei distributions at 400 m a.s.l on the various stability criteria.

FIELD MEASUREMENTS

a. Nuclei measurements

The airborne measurements of ice nuclei within the framework of this work, were carried out mainly with the NCAR acoustic continuous ice nucleus ice counter, Langer et. a. (1967) the main reason for using this instrument, in spite of its inaccurate quantitative performance was its real time recording of the variations of ice nuclei concentrations in a conveniently readable form.

Comparative measurements, directed at an experimental calibration of the NCAR counter, Steele et al. (1967), suggest that this counter consistently counts 16 - 52% of the nuclei registered by a mixing cloud chamber. Therefore they suggest a mean correction factor of 3, for concentrations of ice nuclei throughout the range of 1-500 lit.$^{-1}$.

Similar comparative measurements were conducted in our laboratory, replacing the mixing cloud chamber technique with our thermal diffusion ice nuclei counter, Gagin and Aroyo, (1969). The counting system of the NCAR counter was modified (report in preparation) with a tendency to make it more sensitive. This resulted in reading counts that, on the average, were higher by a factor of 1.7 than those obtained by the unmodified counting system. The mean value of the ratio of the readings of this modified acoustic counter to our filter method was found to vary between 0.3 - 1.5 with an average value near unity and a median value of 0.7$_1$. These comparisons were confined to concentration lower than 10 lit.$^{-1}$. The results of the measurements with the NCAR counter reported in this work are those obtained after the introduction of the above mentioned modification.

b. AgI tracking measurements

Airborne measurements using the NCAR acoustic counter were performed in the area downwind from a single isolated ground based generator. The routine procedure was first to fly upwind from the generator to get an estimate of the background concentration of ice nuclei at certain altitude and temperature. Later an effort was made, while flying at a constant altitude to locate the plume. Once this was done, measurements of ice nuclei concentrations continued in flying along parallel crosswind lines at gradually increasing downwind distances from the source. This scanning was later continued in the same area and altitude on a more limited scale at downwind parallel lines. The ultimate aim was to map the distribution of ice nuclei concentrations and determine plume dimensions at that specific altitude. If the meteorological conditions seemed to be more or

less constant, another altitude was selected depending on the nature of the measured concentrations at the preceding scan. High concentrations at this previous scan lead to measurements at higher altitudes. Finally, within a period not exceeding an hour, data which made possible the determination of the distribution at a constant altitude, of the emitted AgI nuclei, were collected.

The realtionships between the measured and the computed values of the concentrations and similarly of the plume dimensions are displayed in figs. 11 and 12 respectively. As can be seen, a generally good agreement exists for conditions defined as slightly unstable for the G.P.D. model and the altitudes of 400 and 600 m a.s.l.

The process of actually locating the boundaries of the plume while flying, was quite easy, as the background concentrations (approx. 0.1 lit.$^{-1}$) were quite low as compared to those obtained at the rapid transition to in-plume concentration that were nearly two orders of magnitude higher.

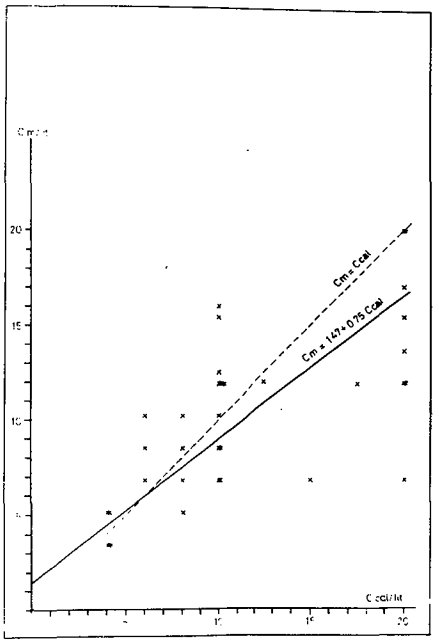

Fig. 11: The regression between the computed (Ccal) and the measured (Cm) concentrations of AgI nuclei active at -15°C emitted from an isolated ground based generator (continuous line).

The relationship between the measured and the computed values for the concentrations was somewhat less clear than the same relationship between plume widths. However, both were good enough to allow the computation of the corresponding regression equations and consequently the correlation coefficients. The latter were found to be surprisingly high, i.e. 0.78 and 0.82 respectively.

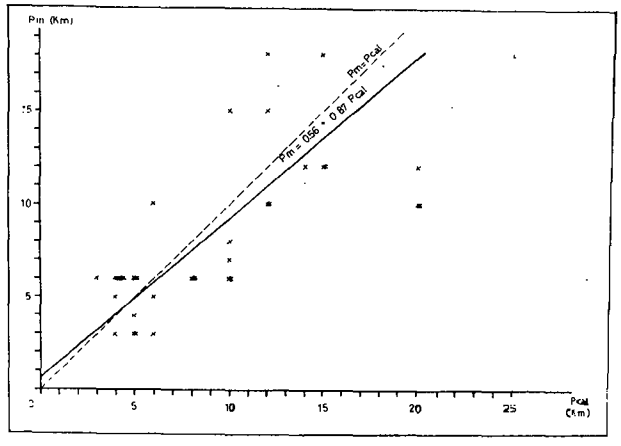

Fig. 12: The regression between the computed (Pcal) and the measured (Pm) AgI plume widths emitted from an isolated ground based generator (continuous line).

DISCUSSION

Regarding the relationship between the measured and the computed values of AgI nuclei concentration, there seems to be a relatively larger scatter of the measured values for a given computed concentration. This kind of a scatter is in our opinion unavoidable when such measurements are performed. It may mainly be attributed to uncertainties as to whether the cross-sections, while flying, were made through the "heart" of the plume at this particular altitude. Secondly, the NCAR counter is known to have a variable performance, within certain limits, which may have also affected the results. It is appropriate to note that, in spite of this scatter, and on the average, there is a surprisingly close correspondence between the regression line, computed for the above mentioned relationship, to that of a line having a slope of 45^0. There seems to be no necessity for any correction factors to the measured values of AgI concentrations. This is quite important in view of the relatively good agreement, obtained previously, between the modified NCAR counter and our thermal diffusion ice nuclei counter. These findings and the even better correspondence of the computed, versus the measured values, of the plume width, fig. 12, suggest that certain conclusions can be drawn.

An assumption is usually applied that, in order for seeding to be efficient, it should provide concentrations of effective nuclei, at cloud base altitudes, that are of the same order of magnitude as of the concentrations of precipitation elements, i.e., 1 to 10 nuclei per liter of air. Typical cloud base altitudes in our region are in the range of 800 to 1000 meters above sea level. As can be seen from fig. 4 the computational model

suggests that for conditions defined as "slightly unstable", only a small fraction of the total area, at the altitude of 800 m, is effected by concentrations that are higher than 4 nuclei per liter. At 1000 m. fig. 5, the effect of seeding is hardly noticeable. Thus, if cloud bases are even higher, an unavoidable conclusion should be drawn, that in such quasi-flat regions, seeding of clouds from ground based generators seems to be inefficient in producing desirable concentrations in large enough areas. On the other hand, the relatively narrow plumes containing significant concentrations, reduce seriously the danger of crosswind contaminative effects in adjacent control areas. These effects, are not negligible if considered downwind from the generators, and especially under stable or neutral atmospheric conditions.

Finally, on the basis of our computations, and sufficiently supporting experimental evidence, it seems that for an efficient area seeding, from the ground and in flat areas, an increased number of generators having higher nuclei outputs are necessary.

ACKNOWLEDGEMENT

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TROPICAL HURRICANES, RAIN STIMULATION AND THEIR EFFECT IN THE RUNOFF OF THE RIVERS IN THE HYDROLOGIC WATERSHED OF NECAXA, Pue.

by

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ABSTRACT

There is a contradiction between the results of the operations of rainfall stimulation valuated by means of the rain precipitations, that denoted a light increment, and the runoff of the Laxaxalpan river, that decreased 30% during the 20 years of the experiment, compared both data with the 20 years before the starting of the project, gives a negative impression of it.

The result of the present study does not only explain the phenomenon, but also confirms the positive balance of the cloud seeding.

THE IMPORTANCE OF THE TORRENTIAL RAINS OF THE TROPICAL HURRICANES IN THE RUNOFF OF THE RIVERS.

The runoff coefficient in a river, specially when it presents strong slopes, has great variations, according with the intensity of the precipitations. In our zone, it could change from 20% with small rains, to 50% in the torrential rains of the tropical hurricanes. For that reason, in the beginning were compared this two elements, choosing like zone of study the watershed of the Laxaxalpan river, that have an area of 700 Km^2, one half of the hydroelectric system of Necaxa. (fig. 1).

By other way, it was considered that the watershed receive the precipitation from the small rains and also from medium precipitations that occurred during the season, when the trade winds are well established, like the torrential ones of the tropical hurricanes that affect extensive zones. The numerical data in monthly averages are given in the next (table 1), well as for the 20 years previous to the operations and for the 20 years of operations:

TABLE 1: RUNOFF OF THE LAXAXALPAN RIVER IN $M^3 X$ S (1)

20 years before the operations:

	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	TOTAL
Monthly average	11.6	13.7	15.8	28.6	29.1	98.8

20 years of operations:

8.5	13.1	12.1	17.9	17.2	68.8
				DEFICIT	30.0 (- 30.0%)

In table II is presented the frequency of tropical hurricanes 20 years before the operations: (3,4,5)

TABLE II.

JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	TOTAL
2	1	9	11	1	24

20 years of operations:

2	1	0	7	1	11
				DEFICIT	13 (- 54%)

To corroborate this overall data, curves were drawn of the frequency of the tropical hurricanes against the runoff of each year, from July to October (fig 2).

The simple examination of the curves show the dependence between the number frequency of the tropical hurricanes and the runoff of the river, that are congruent, with the exception of 3 years out of 40, that presented very special meteorological conditions.

For this reasons, it must concludes that the deficit in the runoff of the Laxaxalpan river was mainly due to the scarcity of tropical hurricanes during the years of operations, and also to the increase of the population and cultivated areas, must have influenced in the phenomenon. By the other way, the precipitations was measured in 3 stations at the north of the watershed (Carmen, Laguna and Los Reyes) located 60 kilometers north given the next figures, in his dependence with the frequency to the tropical hurricanes, to the entire Necaxa watershed, if it is considered the magnitude of the tropical disturbances.

Another curve can be seen in graph of fig. 2, corresponding to precipitation values. Its variations from one year to another also have dependence with the frequency of tropical hurricanes. The averages of the periods are the following: (2)

TABLE 2. SEASONAL AVERAGE OF THE PRECIPITATION (June to October)
(Stations: Carmen, Laguna and Los Reyes)

20 Years before the operations	1168 mm	
20 Years during the operations	1172	
INCREMENT	4 mm	(.3%)

This last figures show that it was not the total amount of rains which had decreased the runoff of the river, but the lack of the torrential rains with high runoff coefficient.

DEDUCTIONS FROM THE GIVEN DATA WITH RESPECT TO THE RAINFALL STIMULATION

Of course next question arise: If the total precipitation was the same before and after the operations, how was it compensated the corresponding torrential rains that did not occur because of the lack of tropical hurricanes?

In the different reports that have been presented concerning the results of the rainfall stimulation in the Necaxa watershed, (6,7) it was concluded that this had been effective to increase the precipitation or to redistributed it, in the small and medium rains of the trade winds not disturbed by cyclonic conditions, while the torrential rains do not show a positive result in the area. Apparently, according to the statistical data, the main increase was in the zones of Apan, Valley of Tulancingo west of the watershed and in the mountainous barrier which limits this at the west. (Fig. 1) This increase agrees with the conclusion of the present study, because if the torrential rains were missed, they were completly compensated with the increase in the normal and small rains in the watershed of the Laxaxalpan river, due to the cloud seeding operations, and the fact that consistently in this zone the days when the burners worked, the amount of precipitation exceeded to the rain in not operated days. (6)

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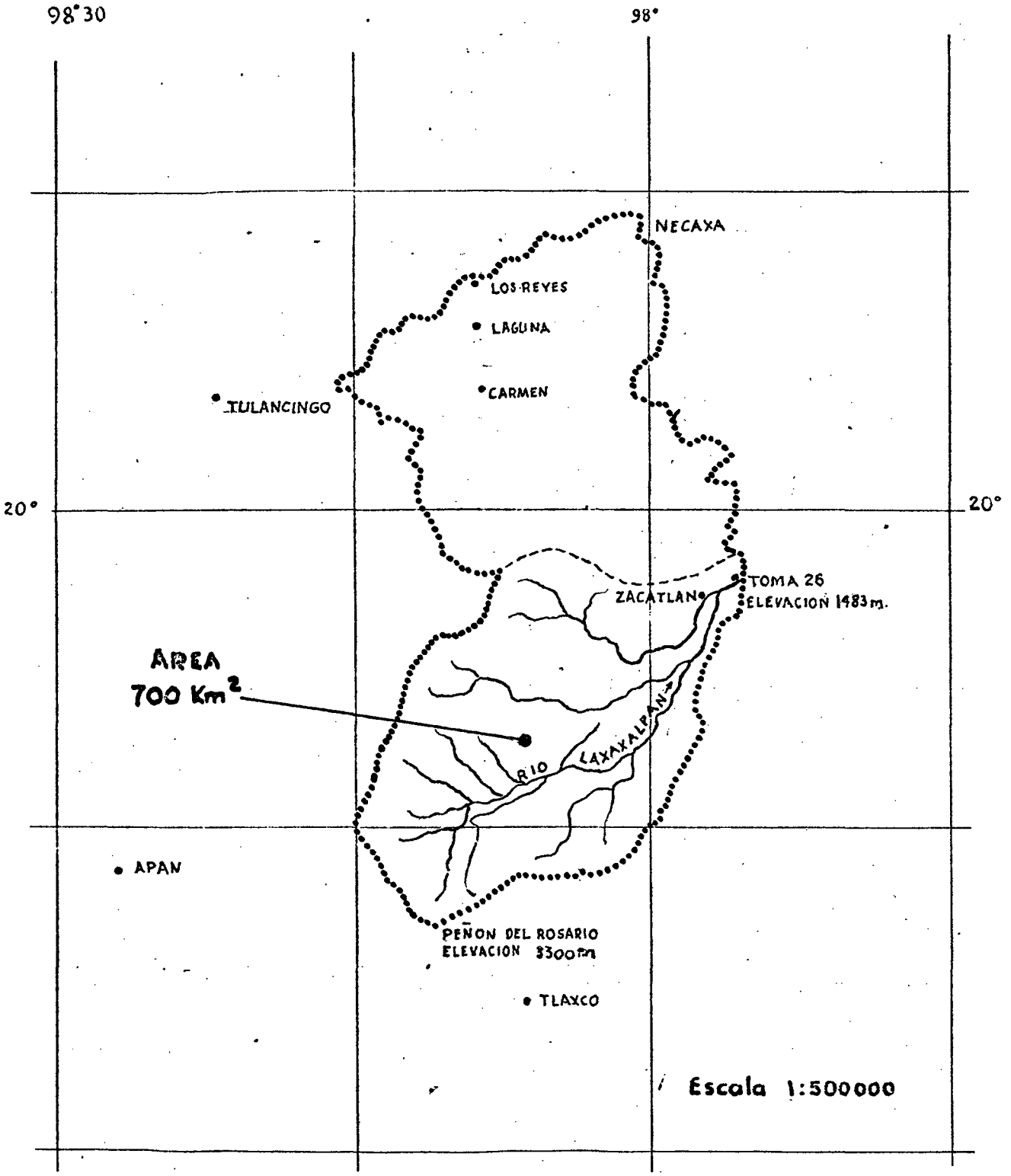

HYDROELECTRIC SYSTEM OF NECAXA, State of Puebla, Mexico

WATERSHED OF THE LAXAXALPAN RIVER

Fig. 1

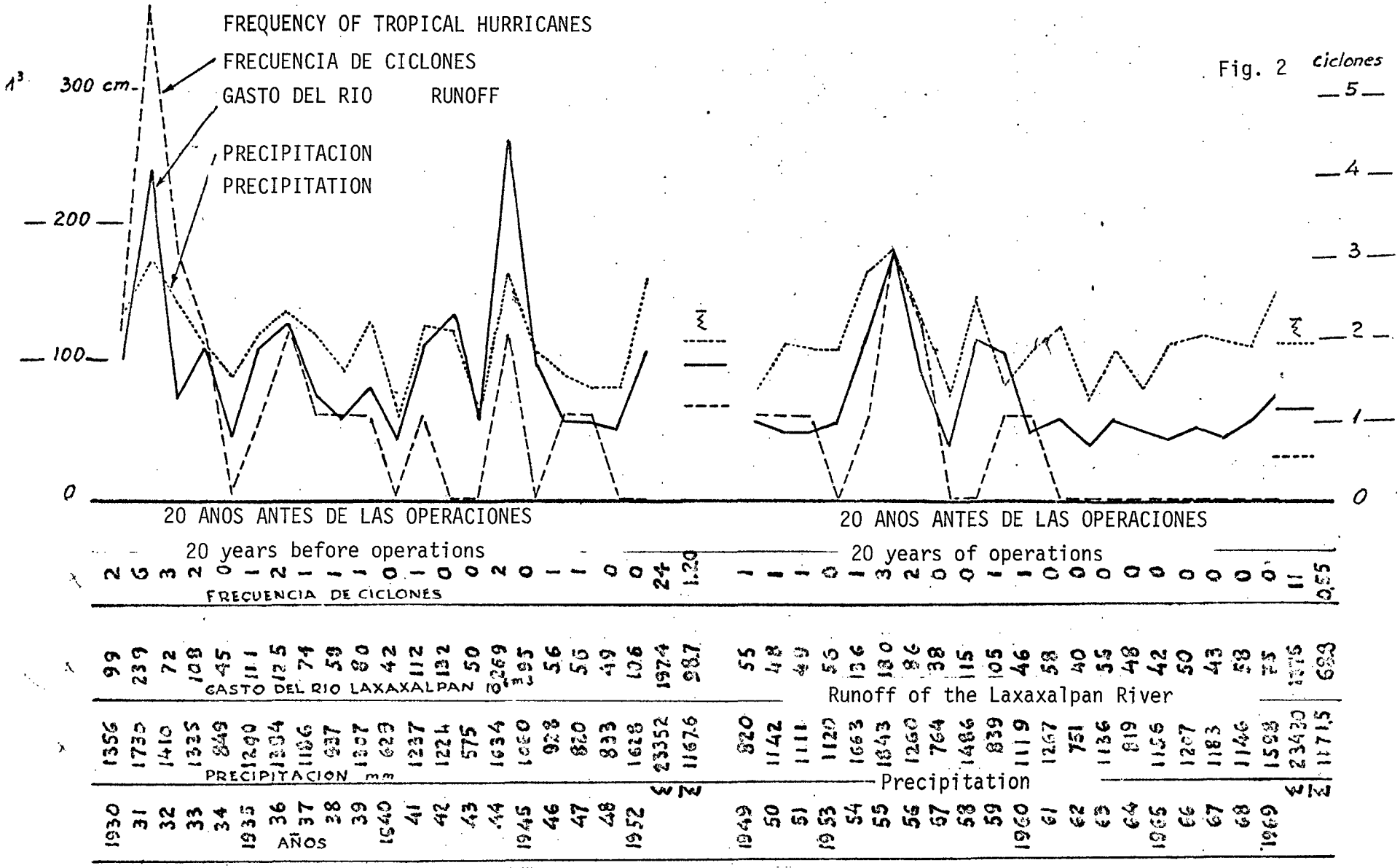

Fig. 2

CORRELATION BETWEEN THE FREQUENCY OF THE TROPICAL HURRICANES, THE RUNOFF OF THE LAXAXALPAN RIVER AND THE PRECIPITATION HYDROELECTRIC SYSTEM OF NECAXA,
State of Puebla, Mexico.

Tabla 2

SEEDING EFFECTS IN CONVECTIVE CLOUDS

IN WESTERN SOUTH DAKOTA

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ABSTRACT

Project Cloud Catcher is a randomized cloud seeding experiment aimed at convective clouds in small, floating target areas. Effects of seeding upon rainfall are evluated on the basis of radar, aircraft, and rain gage observations. Computers have been used in the reduction of the radar and aircraft data.

Both silver iodide and salt seeding cause first echoes to appear at lower elevations than in unseeded clouds, with salt having a more pronounced effect. Radar estimates of rainfall from test cases stratified in terms of cloud height suggest that both seeding treatments are associated with increased rainfall from the test cases, but the results are not judged statistically significant. Consideration of rainfall from a rain gage network on those days when all clouds were considered as candidates for seeding treatment also suggests that salt seeding produces substantial increases in rainfall.

1. INTRODUCTION

This report describes the first three years of a randomized experiment intended to help clarify the manner in which seeding influences precipitation processes in summer convective clouds of the Northern Great Plains.

The evaluation of experiments on convective clouds is rendered difficult by the fact that the clouds often are merged in clusters. Radar would appear to be an ideal means of detecting seeding effects in such clouds, but its use has been limited in the past by the lack of a way to define test case units objectively and by the magnitude of the task of analyzing radar data recorded by hand or by time-lapse photography. By the end of 1968, both of these limitations appeared to have been overcome in the radar facility of the Institute of Atmospheric Sciences east of Rapid City, where an on-line computer had been used to receive and store on magnetic tape radar data processed by a profiler device (Smith and Boardman, 1968). Accordingly, Project Cloud Catcher was set up for the summer of 1969 and continued in 1970-71 to explore the potential of the radar-profiler-computer system in evaluating seeding experiments on convective clouds.

2. PROJECT DESIGN AND EQUIPMENT

2.1 General Remarks

Project Cloud Catcher involves the experimental seeding of convective clouds and the evaluation of results with the aid of data collected by radar, instrumented aircraft, and a rain gage network.

2.2 Definition of Test Cases

The project utilizes movable target areas. Test cases are declared on clouds ranging from small, isolated cumulus to towering cumulus already showing radar echoes.

In 1969 and 1970 the test cases were defined in terms of a grid which extended to 35 n mi in all directions from the radar facility (Fig. 1). The squares were 10 n mi on a side and one square was centered on the radar site. This square was not used as part of the test area because of radar scanning limitations. A test case occupied at any moment two squares of the grids and was allowed to move through the grid.

In 1971 test cases were assumed to be circular. A test case was defined at any time by three parameters, the distance and bearing of the center from the radar, and the diameter. Any diameter up to 20 n mi can be specified and the range to the center of the storm can be any distance between 10 and 50 n mi.

In 1969 and 1970 test cases lasted one hour. In 1971 each test case again lasted for one hour, but official beginning time was delayed 10 minutes from the time of selection in order to give the seeding treatment time to modify cloud characteristics before the collection of data for evaluation was begun. Data were collected in the delay period for stratification purposes and as input to cloud models.

2.3 Choice of Seeding Treatments

It is well known that convective clouds of the Northern Great Plains contain strong updrafts. These strong updrafts do not give a cloud much time to develop precipitation before the wind shear begins to blow off the upper portion of the cloud. Unseeded clouds are often observed to be slow in developing significant precipitation (first 15 to 45 minutes of cloud life), but once precipitation begins to fall through the base a cloud may remain efficient as a rain producer for the remainder of its life.

Three years of randomized silver iodide seeding on the Rapid Project the predecessor of Project Cloud Catcher, showed increases in precipitation for days with small amounts of rain and possible decreases on days with large amounts of rain (Dennis and Koscielski, 1969). The objective of the Rapid Project seeding was to initiate precipitation by the Bergeron process through the introduction of one ice nucleus per liter effective at -10C into the updrafts of convective clouds. Dennis and Koscielski (1969), in discussing the apparent rainfall decreases on stormy days,

suggested overseeding on those days, when cloud tops are often colder than -40C and natural ice crystals are abundant.

Project Cloud Catcher has been used to test two alternative ways to modify convective clouds; first, the stimulation of cloud growth by heavy silver iodide seeding to release latent heat and, second, the release of collodial instability by seeding with finely ground sodium chloride. Previous experiments in South Dakota provided some hope that both methods would be effective on occasion (Donnan and Schleusener, 1968; Schock, 1968).

The test cases of 1969 and 1970 were randomly allotted to no-seed, silver iodide seed, and salt seeded classes with a one-third probability for a given test case to fall in any one class. In 1969 each test case was treated independently, but in 1970 the treatment randomly selected for the first case of the day was applied to subsequent cases on that day. This was done to minimize possibilities of contamination and to permit evaluations with rain gage data (Sec. 2.6 below).

There was a slight change in selection of seeding treatment in 1971. Operational days and the seeding treatment for each day were selected in the morning on the basis of cloud modeling studies. The project meteorologist provided a forecast sounding of airmass conditions expected around 1700 MDT. The Hirsch (1971) steady-state cloud model, described briefly in Sec. 3 below, was run with the forecast sounding for updraft radii of 0.5, 0.75, 1.0, 1.5, and 2 km for an unseeded and a silver iodide seeded cloud (total glaciation at -8C). Output from the model included the maximum expected updraft for unseeded clouds and the increase in cloud height which would result from silver iodide seeding. The following parameters were determined from the model output:

R_w: radius at which the maximum vertical velocity for an unseeded cloud is greater than 10 m sec^{-1}.

R_s: smallest radius which gives a height increase of 500 meters due to silver iodide seeding.

R_l: largest radius which gives a height increase of 500 meters due to silver iodide seeding. (All R's refer to updraft radius at cloud base.)

The decision making process is summarized in the flow chart, Fig. 2. If the model output showed that updrafts in excess of 10 m sec^{-1} should be present in unseeded clouds with updraft radii as small as 1 km, a salt day was declared. On those days when an updraft in an unseeded cloud of radius 1.0 km did not exceed 10 m sec^{-1}, attention was turned to silver iodide seeding. If the model indicated height increases of 500 meters or more for any of the updraft radii under 2 km, a silver iodide day was

declared, with one-third of the cases reserved as no-seed days.

2.4 Aircraft and Seeding Equipment

In 1969 a Piper Apache was used as an instrumented cloud penetration platform, but because of performance limitations it obtained few data of interest. In 1970 and 1971 a Piper Aztec was used with better results. It carried a digital tape recording system; the taped data were reduced on the School's PDP-8 computer.

During all years a Beech Baron was used for the seeding. It was equipped with a Lohse generator and a flare rack on each wing. The flares contained 120 gm of silver iodide each and had a 5-minute burn time. Up to six flares were used per test case. The Lohse generators were used as backup equipment for the most part. They burned a 4%-by-weight solution of silver iodide in acetone. Sodium iodide was used as the carrier in 1969 and ammonium iodide in 1970. In 1971 only flares were used. The aircraft was also equipped with a 400 lb salt hopper. Salt was released at rates of 100 to 200 lb in 20 minutes in the updrafts below cloud base. The salt used was a mixture of two kinds, Morton's 200 with median mass diameter in the 10 to 20 μ range and SolStar with median mass diameter in the 50 to 150 μ range.

An Aztec aircraft from Meteorology Research, Incorporated carrying special cloud physics instrumentation was operated on the project from 6 July to 23 July of 1971.

2.5 Role of On-Line Computer

A PDP-8 computer with disk, magnetic tape, and a storage display unit is used as a radar data logging device. The computer plays a dual role, providing real-time displays of selected data as a guide to operational decisions and recording data on magnetic tape for subsequent analysis.

The radar information for 1969 and 1970 was obtained from a 3.2-cm radar with a 1.2^0 pencil beam, which was scanned through the test case approximately once every 7 minutes. Radar data were passed to a profiler device which derived the logarithm of mean echo power received from each of 17 range gates along the beam and passed this information to the computer in analog form. These radar data and analog information about antenna coordinates were read by the computer through an analog-to-digital converter.

Values of Z_e, the equivalent radar reflectivity factor, were computed and logged using a rectangular coordinate system with horizontal resolution of 0.5 n mi for each 5,000-ft increment of height from 10,000 ft to 45,000 ft (Fig. 3). Thus, data were logged from 3200 positions within each square and from 6400 positions for each complete scan, as a test case occupied two squares. The data were stored in a fast-access disk file through a buffering scheme in the computer memory which was used to reconcile the rectangular coordinate system with the conical scanning pattern of the radar.

At the conclusion of each scan data were transferred from the disk through the computer to magnetic tape for permanent storage. The taped data were used later for computer analysis of the storm and also to generate oscilloscope displays which permit one to review the history of the test case and view horizontal and vertical sections as desired.

In 1971 a 10-cm FPS-6/18 S-band radar system was used to gather the radar data. The FPS-6 antenna yielded improved vertical resolution but the beam was over 3^0 wide in the horizontal. A digital integrator served as the interface between the radar and the computer. As noted in Sec. 2.2 above, a test case was defined in terms of range and azimuth to its center and its diameter. The radar was operated in sector scans at stepped elevations to cover each test case. Data were converted to cylindrical coordinates and logged with 1 n mi horizontal resolution along the beam and 2500 ft vertical resolution on 25 azimuths intersecting the test case. Data were logged at ranges from (c-10) n mi to (c+10) n mi, where c is the range to the center of the test case. A complete scan of a test case was obtained every 3 to 5 minutes. Real-time computer displays of the radar data were generated.

2.6 Area Rainfall Analyses

The project area was instrumented with 108 rain gages in 1970 and 1971. The work plans for 1970 and 1971 called for a comparison of data from the rain gage network for no-seed, silver iodide seed, and salt seed days. (This was not possible in 1969 because all test cases were randomized independently.) The project meteorologist had the option of calling an area test day if active convective clouds were widespread. As the meteorologist did not know if a day was to be a seed day or not, there was no bias in the selection of area test days.

3. CLOUD MODELING STUDIES

3.1 Development of the Hirsch Cloud Model

In parallel with the Cloud Catcher field program, the Institute has conducted a number of cloud modeling studies to help in the selection of seeding treatments and the interpretaion of results. The value of cloud models in the interpretation of results of seeding experiments has been clearly demonstrated by Simpson et al. (1965), Weinstein and MacCready (1969), and others.

Since the application of the Weinstein and Davis model to atmospheric soundings in the Rapid City area during 1967 and 1968 yielded only fair agreement with actual cloud development (Davis et al., 1969), modeling work under Project Cloud Catcher began with attempts to adapt the model to conditions of the Northern Great Plains.

The Weinstein-Davis model is a steady-state one-dimensional numerical model that predicts cloud development on the basis of an environmental sounding and initial updraft radii. The Hirsch (1971) model, developed from the Weinstein-Davis work, includes a linear freezing function for cloud water based on Squires and Turner (1962), a temperature change due to freezing after Saunders (1957), and Berry's (1968) autoconversion techniques for cloud water. Graupel water is incorporated in the moisture balance equations after Wisner (1970); it is formed by accretion of cloud water and hydrometeor water as well as conversion of cloud ice and hydrometeor water. The hydrometeor water and graupel are permitted to fall as precipitation after the techniques developed by Simpson and Wiggert (1969).

The moisture regime is depicted in Fig. 4. In the lowest region of the cloud, from cloud base to -8C, cloud water and hydrometeor water are formed. In the second layers, from -8C to a glaciation temperature specified in advance (usually -25C), graupel is allowed to form in addition to the cloud water and hydrometeor water. From the glaciation level to -35C cloud ice is permitted to form from the cloud water through a linear freezing function, while graupel water, cloud water, and hydrometeor water continued to form and coexist. In the uppermost part of the cloud, from -35C to the point where the vertical velocity of the air goes to zero, water is present in solid forms only (graupel and cloud ice). The microphysical processes are pictured in the block diagram of Fig. 5.

Output of the numerical model is in the form of vertical profiles of updraft velocity, total water content, temperature excess, cloud water, cloud ice, hydrometeor water, graupel water, and radar reflectivity.

3.2 Modeling of Microphysical Processes

A non-steady-state one-dimensional model of a growing convective cloud has been developed to study the growth of hailstones by Musil (1970). Vertical velocity and liquid water content profiles change at a predetermined rate, beginning with small values and gradually increasing to steady-state values that might be expected in a mature thunderstorm.

Hailstone growth equations used in the model are developed in terms of the well known dry- and wet-growth regimes (Ludlam 1958), but include terms that account for growth in a mixture of supercooled cloud droplets and ice crystals. Hailstone embryos in the form of liquid cloud droplets can be introduced into the model at various heights and times, and the subsequent trajectories analyzed. The growth of various hail or rain embryos can be tested with different updraft magnitudes and shapes. An unfrozen particle reaching 5 mm diameter is assumed to break, yielding particles with one-half the original diameter, after which one of the particles is followed. The hail embryos are assumed to freeze at -15C and the cloud water freezes at a nonlinear rate between -20 to -40C. Output of the numerical model includes the height, radius, mass (in both liquid and solid form), terminal velocity, and growth rate, all as functions of time.

diameter appear suitable for small clouds with maximum updrafts of 10 to 15 m sec^{-1} and particles of 50 to 100 μ for clouds with maximum updrafts over 20 m sec^{-1}.

The growth model has recently been used in combination with the Hirsch model. Liquid Cloud droplets of various sizes, simulating salt seeding, have been introduced into the model and their subsequent growth analyzed. Figure 6 is a sample plot of drop size and height with respect to time.

4. ANALYSIS OF RESULTS

4.1 Method of Analysis

The analysis of results is given in four parts; namely, (1) first echo study, (2) radar rainfall analysis, (3) area rainfall analysis, and (4) hailfall analysis.

4.2 Study of First Echoes

The heights of all identifiable first echoes were tabulated from the horizontal section printouts. Where echoes appeared simultaneously at several levels, the first echo was defined by selecting the level with the highest reflectivity factor as the height of first echo. Comparison of heights determined in 1970 in this way with some recorded (for the same echoes) manually from the RHI display of the FPS-6/18 S-band radar showed good agreement.

Only echoes occurring more than 10 minutes after the declaration of a test case were used in the analysis. The resulting sample consisted of 111 unseeded echoes from 19 different days, 34 silver iodide seeded echoes from 9 different days, and 91 salt seeded echoes from 18 different days. In a search for evidence of seeding effects temperature of first echoes and their heights above cloud base (Table 1; Figs. 7 and 8) were analyzed.

TABLE 1

Summary of first-echo samples from unseeded, silver iodide seeded, and salt seeded Cloud Catcher cases

	Unseeded	Silver Iodide	Salt
No. first echoes	111	39	91
Average cloud base temperature (C)	+10.3	+9.5	+9.9
Average value of max. updraft in cases sampled by aircraft ($m\ sec^{-1}$)	18	16	17
Average value of max. updraft from model ($m\ sec^{-1}$)	19	17	17
Median first-echo temperature (C)	-13	-6	0
Median height above cloud base (ft)	10,000	6,700	4,500

The median temperature is -13C for unseeded echoes, -6C for silver iodide seeded echoes, and 0C for salt seeded echoes (Fig. 7). The median height above cloud base is 10,000 ft for unseeded clouds, 6,700 ft for silver iodide seeded clouds, and 4,500 ft for salt seeded clouds (Fig.8). The differences among the three classes strongly suggest that salt and silver iodide have appreciable cloud physics effects and are responsible for the appearance of many first echoes in seeded clouds.

4.3 Radar Rainfall Estimates

Rainfall in the test cases of 1969 and 1970 was estimated by converting equivalent radar reflectivity factors (Z_e) at 10,000 ft to rainfall rates by $Z_e = 200R^{1.6}$, where Z_e is in mm^6/m^3 and R is the rainfall rate in mm/hr. The same formula was used in 1971 for values of Z_e up to 42.5 dBz, but for higher values the formula $Z_e = 55.4R^{2.05}$ was used (Miller 1971).* The Miller formula is based on climatology of 5-min rainfall rates in western South Dakota and is more accurate (for 10-cm data) than the $200R^{1.6}$ formula when hail is present.

Rainfall rates estimated from the first scan were assumed to extend back to the start of the case; rainfall rates estimated from the last scan were assumed to apply to the end of the case, and periods between radar scans were divided equally between the scans.

*Personal communication.

No attempt was made to correct for attenuation; there is some evidence that the attenuation with the X-band system in 1969 and 1970 was roughly offset by the tendency toward high Z-values due to the presence of hail, although the rainfall was likely overestimated in some cases with hail. The change to a 10-cm set in 1971 eliminated serious attenuation and the use of the Miller Z-R relationship helps reduce the problem of overestimates of rain in the presence of hail. However, if there is a hail suppression effect due to seeding with either silver iodide or salt, the results in this section are biased against the detection of possible rainfall increases due to seeding.

An analysis is presented in Table 2 where the average rainfall per test case is shown for the three seeding treatments and for intervals of cloud height. Cloud heights have been taken from radar data in most cases; heights of non-echoing clouds were taken from aircraft data or from time-lapse photographs. It is apparent that total rainfall from a storm increases rapidly with the height of the storm.

TABLE 2

Average rainfall (acre-feet) per test case by seeding treatment and cloud height, and ratios with repect to average rainfall for no-seed cases in same height interval. Number of cases in each category shown in parentheses.

Cloud Height (kft)	Seeding Treatment			Ratios
	No-Seed	AgI	Salt	NS/AgI/Salt
$\geq$ 36	760(10)	1500(3)	1180(7)	1.0/2.0/1.5
31-35	270(7)	530(3)	790(14)	1.0/1.9/2.9
26-30	460(9)	70(6)	170(8)	1.0/0.2/0.4
$\leq$ 25	10(13)	60(12)	20(12)	1.0/6.3/2.4

There is some indication that seeded storms produce more rain than do the unseeded storms, but the limited number of test cases precludes firm conclusions. The seed/no-seed ratios of Table 2 are favorable for most cloud height intervals. As the ratios vary somewhat, Table 3 was developed to get some idea of the effects of seeding all clouds with either salt or silver iodide. The figures were calculated by assuming the averages shown in Table 2 would have applied to all clouds in the particular height interval had they fallen into the treatment category in question. The seed/no-seed ratios are 1.39 and 1.40 for AgI and salt respectively. Because of the large random variations in rainfall per case, these data are not yet statistically significant but they do indicate possible increases of 40% due to seeding.

TABLE 3

Calculated total rainfall (acre feet) from no-seed, AgI seed, and salt seed cases assuming all clouds had been (1) not seeded, (2) Agi seeded and (3) salt seeded. Number of cases shown in parentheses.

		Seeding Treatment	
Cloud Height	No-Seed	AgI	Salt
$\geq$ 36	15200(20)	30000(20)	23600(20)
31-35	6480(24)	12720(24)	18960(24)
26-30	10580(23)	1610(23)	3910(23)
$\leq$ 25	370(37)	2220(37)	740(37)
Total	33630	46550	47210
Ratio	1.0	1.39	1.40

4.4 Area Rainfall Analyses

Twenty-one days of 1970 and 1971 were area test days. Nine were no-seed, eight were salt seed, and four were silver iodide seed days. It should be noted that area test days in 1971 were more apt to be salt days than silver iodide days under the treatment selection rules (Sec. 2.3).

Table 4 gives the total of the 12-hr rainfall observations made at 2000 MST and average rain per gage with rain for each area test day for the three categories. The total rain at all gages in the network for the nine no-seed days was 43.12 inches, for the four silver iodide seed days, 9.80 inches, and for the eight salt seed days, 75.45 inches. The daily average of the total of the observations was 4.79 inches for the no-seed days, 2.45 inches for the silver iodide seed days, and 9.43 inches for the salt seed days. The average rain per gage with rain was 0.185 inches for no-seed, 0.209 for silver iodide, and 0.213 for salt. The average rain per gage with rain is almost the same for the three categories, but the total rain per day is much larger on salt seed days. A Wilcoxon Rank test shows salt versus no-seed days different at the 15% level of significance (two-tailed test).

TABLE 4

Sum of rainfall observations and average rain per gage with rain for area-test days

Date	Total Rain (in)			Average Rain per Gage with Rain (in)		
	No-Seed	AgI	Salt	No-Seed	AgI	Salt
6/8/70	2.41			.127		
6/9/70			2.31			.068
6/18/70	2.83			.113		
6/24/70	5.47			.171		
7/6/70		.41			.137	
7/7/70		1.04			.208	
7/8/70			15.36			.244
7/9/70	.71			.142		
7/17/70			.22			.037
7/22/70	.27			.054		
7/28/70	.95			.136		
7/31/70	1.61			.180		
8/5/70			28.20			.513
8/6/70	27.91			.620		
8/11/70		5.24			.308	
6/9/71			11.76			.326
6/17/71			8.95			.248
7/9/71			4.20			.135
7/22/71	.96			.120		
8/9/71		3.11			.183	
8/13/71			4.45			.131
Total	43.12	9.80	75.45	1.663	.836	1.702
Average per day	4.79	2.45	9.43	.185	.209	.213
Ratio	1.0	0.5	2.0	1.0	1.1	1.1

Table 5 shows the area seed days' results ranked in terms of the maximum updraft in cloud as predicted by the Hirsch cloud model. Table 5 gives an indication of maximum area rainfall occurring with updrafts in the 18-22 meter/second range and lesser amounts for both weaker and stronger updrafts. The sample is too small for the results to have statistical significance.

TABLE 5

Rainfall from area-test cases ranked according to maximum updraft 1969-71 data

Max Updraft (m/sec)	Seeding Treatment	Rain fall (in) Total	Rain fall (in) Ave. per Gage with Rain
31	Salt	4.20	.140
28	AgI	5.24	.308
26	No	2.41	.127
24	No	0.95	.136
22	No	5.47	.171
22	Salt	28.20	.513
21	No	27.91	.620
20	Salt	15.26	.244
19	No	0.27	.054
19	Salt	2.31	.068
18	Salt	11.76	.330
17	AgI	0.41	.137
17	Salt	8.95	.250
16	No	0.71	.142
14	No	1.61	.180
14	Salt	4.45	.130
13	No	0.96	.120
10	AgI	1.04	.208
10	Salt	0.22	.037
9	No	2.83	.113
9	AgI	3.11	.180

4.5 Analyses of Hailfall

Each case was analyzed for hail on the basis of a foil impactor network of 108 stations. The hail is broken into four categories: 0), no hail; 1), light hail (less than 20 ft-lbs/ft^2); 2), moderate hail (20-50 ft-lbs/ft^2); and 3), heavy hail (greater than 50 ft-lbs/ft^2).

There was little hail damage associated with the test cases. The two exceptions were heavy hail with Case 69-31 on July 23, 1969, which was a no-seed case, and Case 71-5 on July 6, 1971, which was a salt seed case, but with the hail cell actually not seeded due to the aircraft

positioning problems.

Table 6 shows the distribution of the test cases in terms of maximum hail intensity recorded at any one station. Thirty-one percent of the no-seeded cases, twenty-one percent of the silver iodide cases, and seventeen percent of the salt cases had hail. The fact that the no-seed cases had more hail is partly related to the taller clouds which occured on those days. Most of the hail fell from clouds with tops above 36,000 ft. There were 10 no-seed cases, 3 silver iodide cases, and 7 salt seed cases in this category. The above statement does not imply that silver iodide seeding or salt seeding did not have an effect on hail but the effects cannot be identified in the present data sample.

TABLE 6

Distribution of cases by seeding treatment and maximum hail intensity recorded

Max. Hail Intensity	Seeding Treatment		
	No-Seed	AgI	Salt
0	27	19	34
1	11	3	3
2	0	2	3
3	1	0	1*
	39	24	41
Percent of cases with hail	31	21	17

*Cell producing hail was not seeded.

0 = No hail
1 = Light hail (less than 20 ft lb/ft^2)
2 = Moderate hail (20 to 50 ft lb/ft^2)
3 = Heavy hail (greater than 50 ft lb/ft^2)

5. CONCLUSIONS

1. First echoes appear lower in seeded clouds than in unseeded clouds with salt having a more pronounced effect than silver iodide.

2. Radar indicates more rainfall from seeded clouds but the differences are not yet statistically significant.

3. Area rainfall analyses show almost twice as much rain on salt seed days as on no-seed days, but silver iodide seed days have yielded less rain than no-seed days. Again the number of cases is too small for statistical significance.

4. Hailfall in seeded clouds appears to be less than in unseeded clouds for both salt and silver iodide, but there were more tall clouds in the unseeded sample so that results are uncertain.

5. Tentative results agree with many previous experiments in South Dakota and elsewhere. We believe the experiment should be pursued with increased emphasis on cloud modeling to help identify seeding effects.

ACKNOWLEDGEMENTS

The research reported herein was supported by the Water Resources Management Division, Bureau of Reclamation, U. S. Department of the Interior under Contract Number 14-06-D-6796. The data logging and data reduction programs were written by Mr. James H. Boardman and Mr. Garth Peterson.

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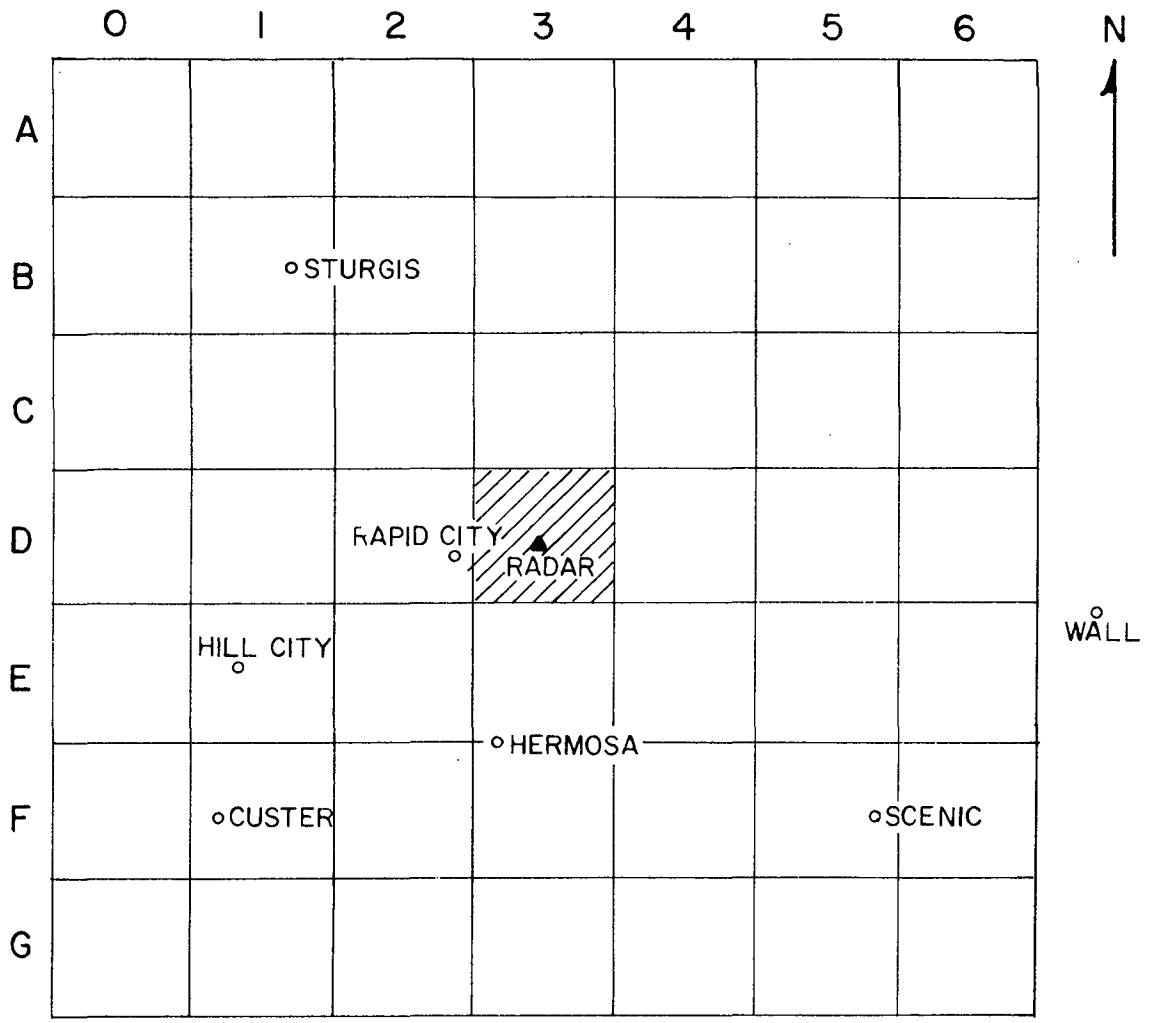

Fig. 1. Grid used in defining Cloud Catcher test cases in 1969 and 1970.

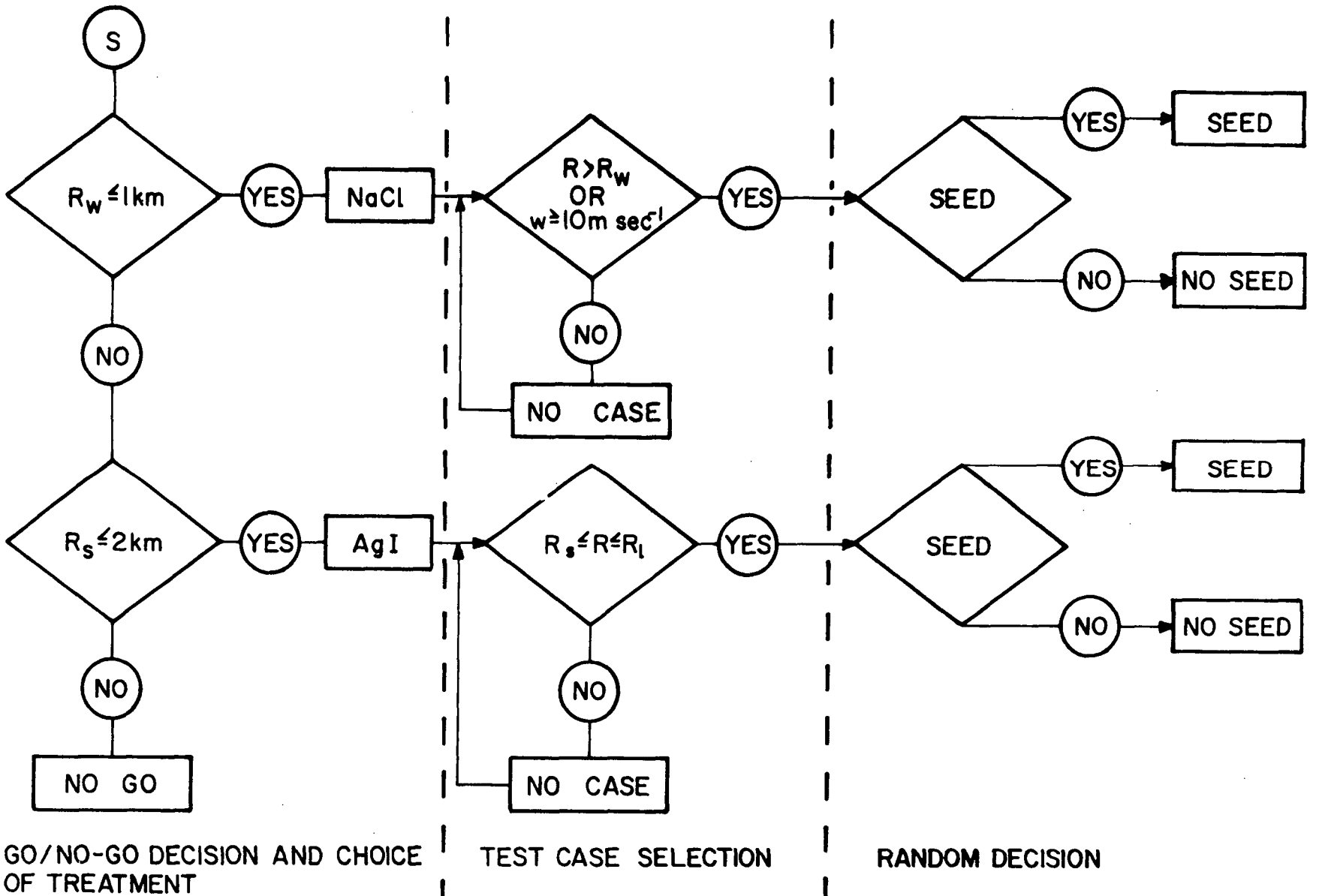

Fig. 2. Flow chart for choice of seeding treatment and test case selection.

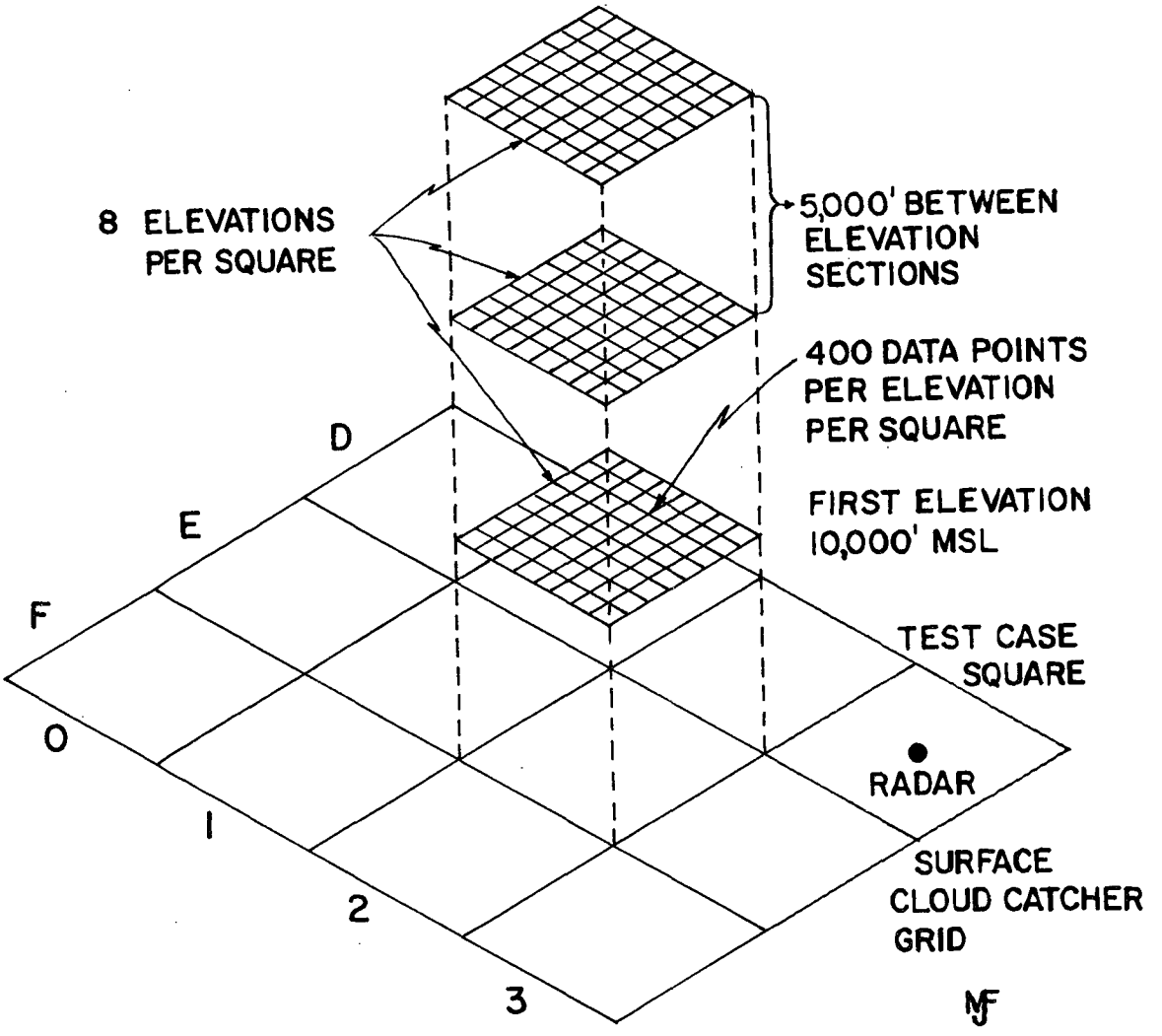

Fig. 3. The coordinate system used for radar data logging in Project Cloud Catcher in 1969-1970.

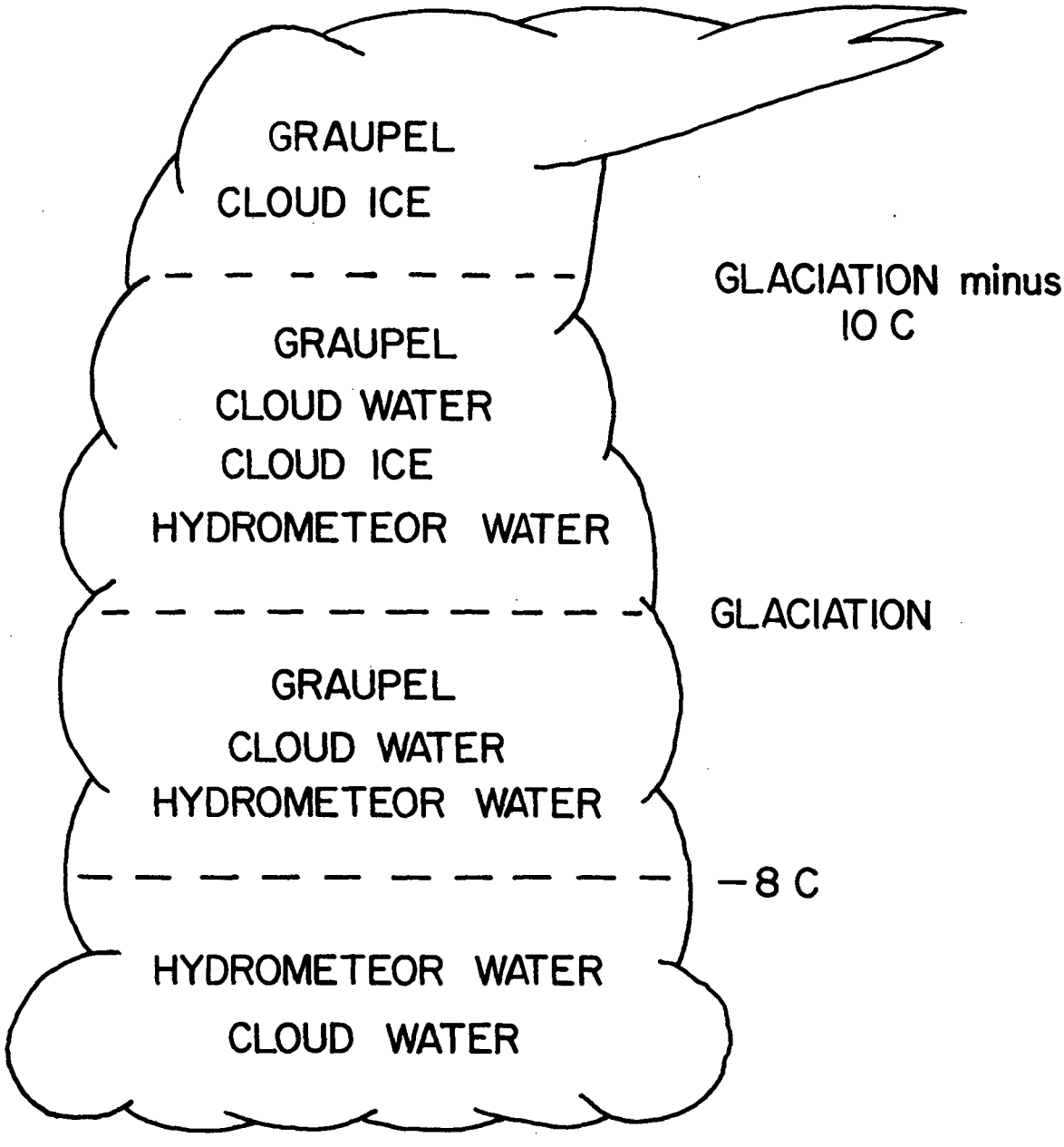

Fig. 4. Moisture regime in one-dimensional steady-state cumulus cloud model.

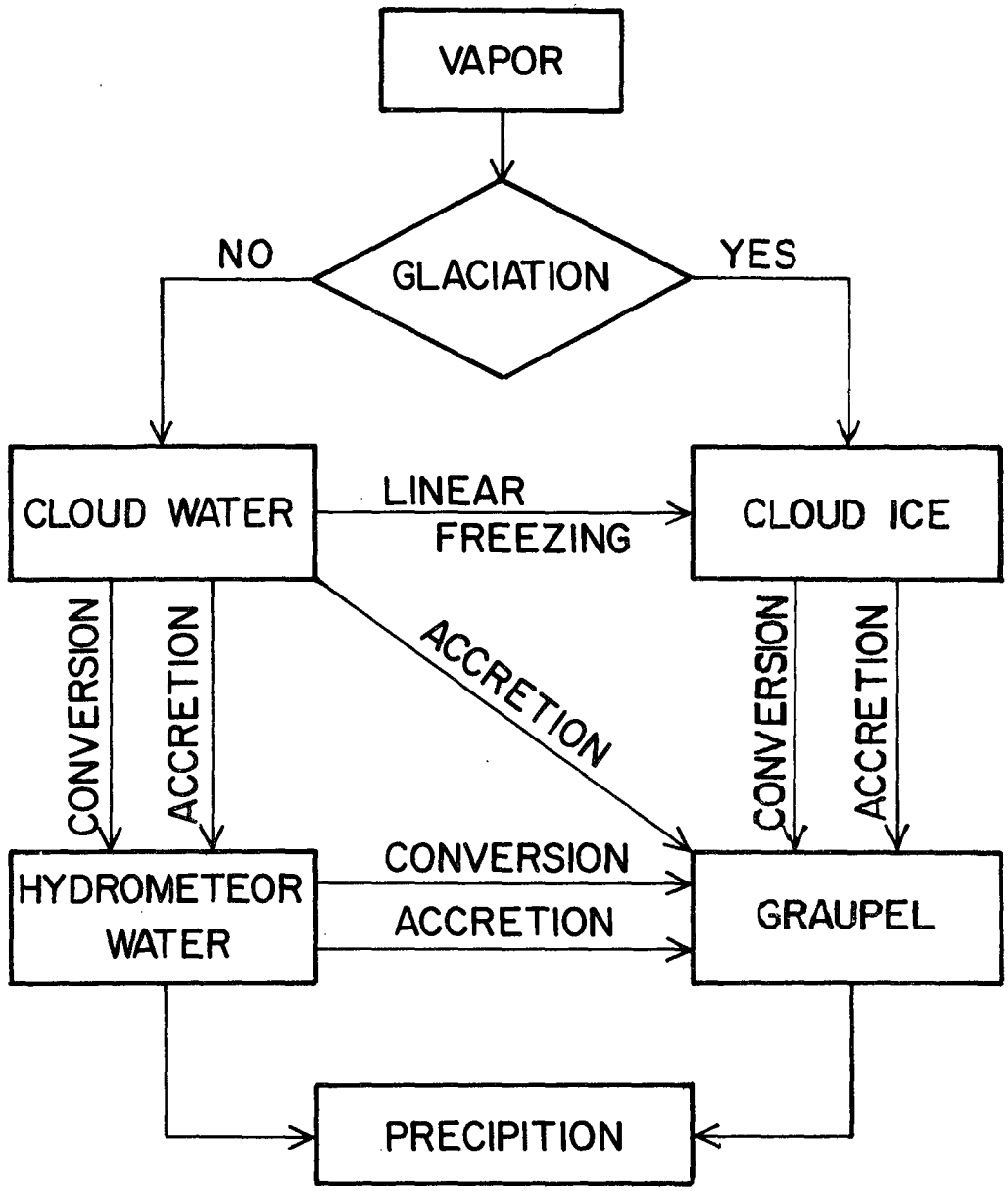

Fig. 5. Block diagram of microphysical processes.

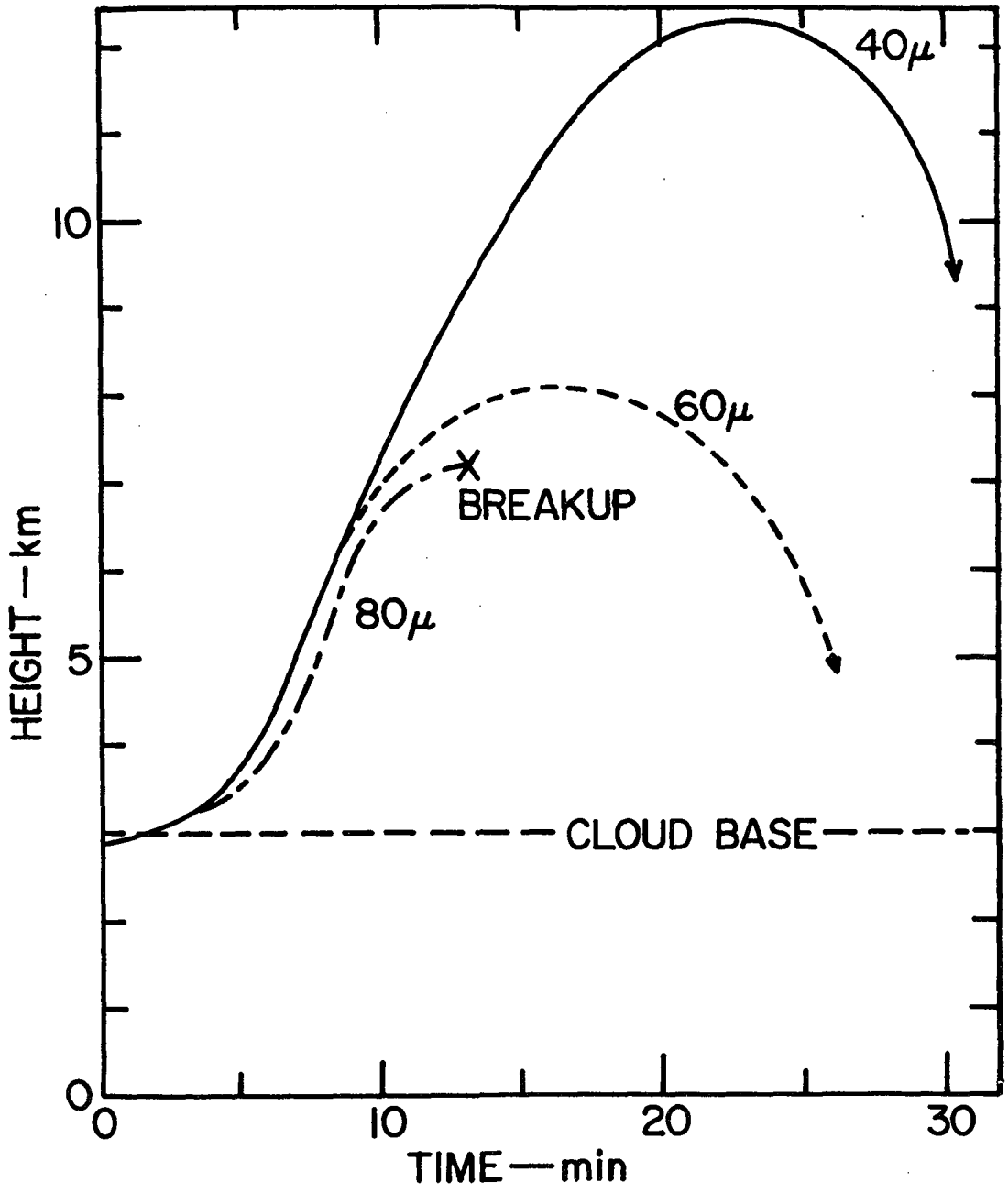

Fig. 6. Computed trajectories for salt particles introduced into cloud of 5 August 1970.

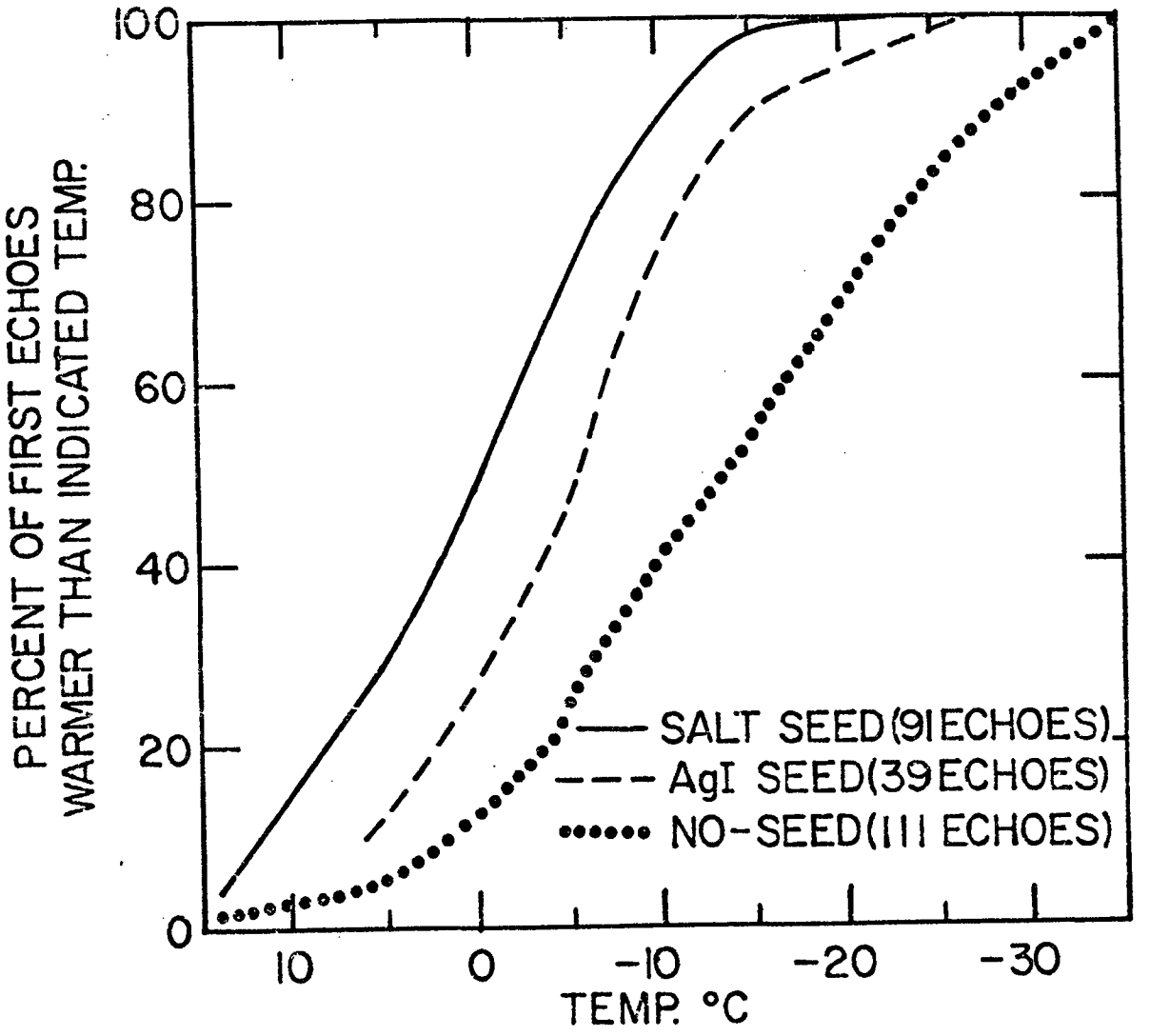

Fig. 7. Cumulative distribution of first echoes with respect to temperature for unseeded, silver iodide seeded, and salt seeded classes.

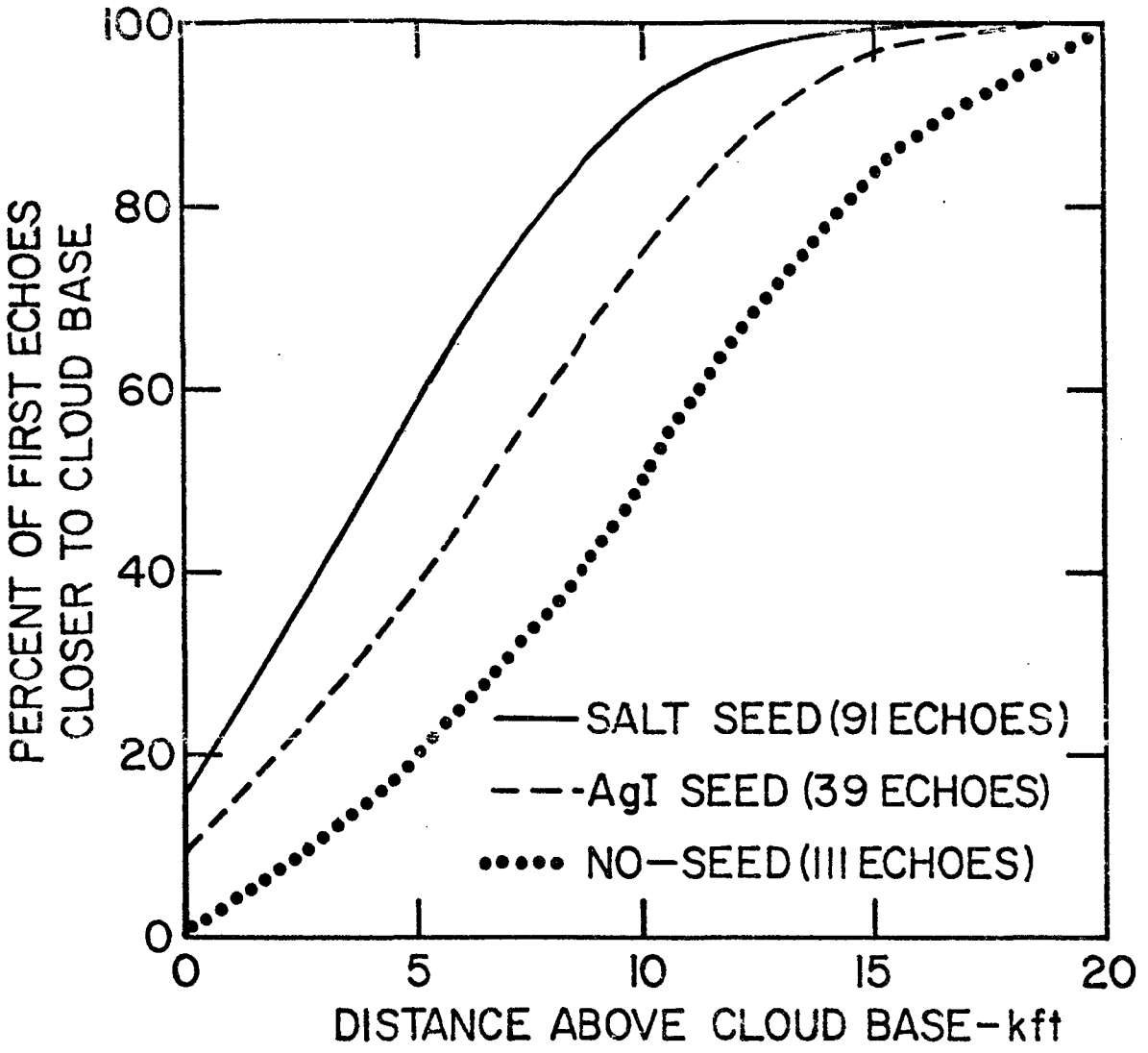

Fig. 8. Cumulative distribution of first echoes with respect to height above cloud base for unseeded, silver iodide seeded, and salt seeded classes.

SOUTH DAKOTA CLOUD SEEDING EVALUATION

1965-1971

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ABSTRACT

Target control analyses of seven county cloud seeding programs in South Dakota (1965-1971) yield adjusted target/control ratios of rainfall from 1.07 to 1.90 in value. Therefore, the rainfall received over each target was more than could be expected to occur naturally by comparison to the rainfall over its control.

Target control analyses for two different areas seeded for hail suppression in 1971 yield adjusted target/control ratios of .99 and .94. Therefore, the hailfall received over each target was very close to that expected to occur naturally by comparison to the hailfall over its control. Small decreases in hailfall are suggested, but it is believed that additional data should be collected and analyzed before drawing any conclusions about effects being obtained.

The use of crop-hail loss-cost data for computing target/control ratios of normal hailfall is found to be feasible.

1. INTRODUCTION

This study employs target/control ratio techniques to evaluate overall effects of cloud seeding on spring and summer rainfall and hailfall in some areas where county commissioners have funded weather modification programs. Rainfall evaluations are made for two areas (Fig. 1) seeded for five or more years, using data obtained from observing stations operated by the National Weather Service, NOAA. Also, rain and hailfall evaluations are made for some areas (Fig. 2 and Fig. 3) seeded for one or two years' duration, using data obtained from specially installed networks of rain gages and hail indicators.

It is well established that cloud seeding with silver iodide in South Dakota can increase rainfall from local showers, but it may reduce

rainfall from severe thunderstorms (Dennis and Koscielski, 1969). It may also reduce hailfalls (Dennis and Schock, 1971). However, the ultimate extent to which clouds can be beneficially modified is not known, and the best procedures and techniques for seeding all types of clouds may not have been developed as yet.

Since proven cloud seeding procedures and techniques for all environmental conditions have not been available to cloud seeders, it appears likely that rainfall may have been increased from some types of clouds but decreased from others, especially since heavy seeding of severe storms for hail suppression has been done quite frequently. The overall effects of seeding for hail suppression are also debatable.

The question, then, is whether the overall effects of this cloud seeding have been to increase or decrease rainfall and hailfall and the magnitude of the changes obtained. The answers to this question will tell the counties whether their expenditures for cloud seeding have obtained the desired results and provide a better basis for estimating the benefits to be obtained in the South Dakota from future cloud seeding programs with improved cloud seeding techniques.

In assessing the target/control ratios obtained by this study it should be kept in mind that their reliability is affected by these factors:

1) Rainfall and hailfall are highly variable from place to place and from season to season. Consequently, natural variations in summertime rainfall over areas the size of a county on a typical year may be greater in magnitude than the effects produced by cloud seeding, and these variations will tend to mask seeding effects. Since hailfall occurs less frequently than rainfall, seeding effects on hailfall may be masked to even a greater extent.

2) All seedable storms within target areas have not always been seeded, and precipitation measurements have not been available in such a form that it could always be determined whether precipitation came from seeded or unseeded storms. Consequently, the data for the two categories have not been separated for this study. For example, precipitation received at night, when only a limited amount of cloud seeding has usually been done, has been lumped in with precipitation received in the daytime. This dilutes the data and makes it more difficult to determine seeding effects.

3) The limited number of rain gages and hail indicators used to obtain measurements in target and control areas provide only a small sampling of the rain and hailfall in these areas. The samples obtained may or may not be representative of an area for a particular month or year. However, as the number of observational points and years of data increase, natural variations in rain and hailfall should begin to average out and seeding effects should be increasingly detectable. The apparent changes detected, however, are not in a form that can be readily tested for statistical significance.

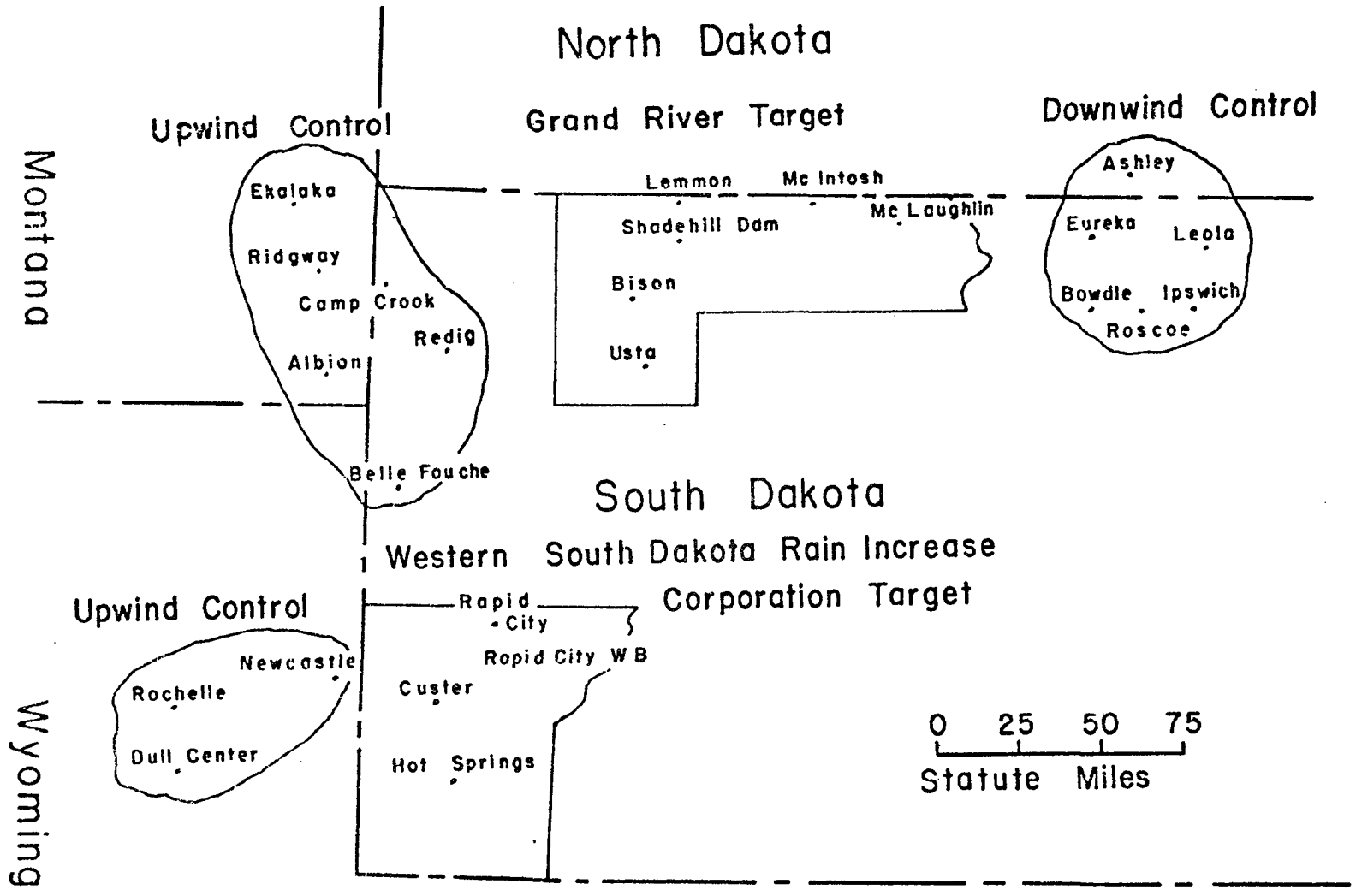

Fig. 1. Map of target and control area stations used for the Grand River Project and the Western South Dakota Rain Increase Corporation (WASDRI) target area.

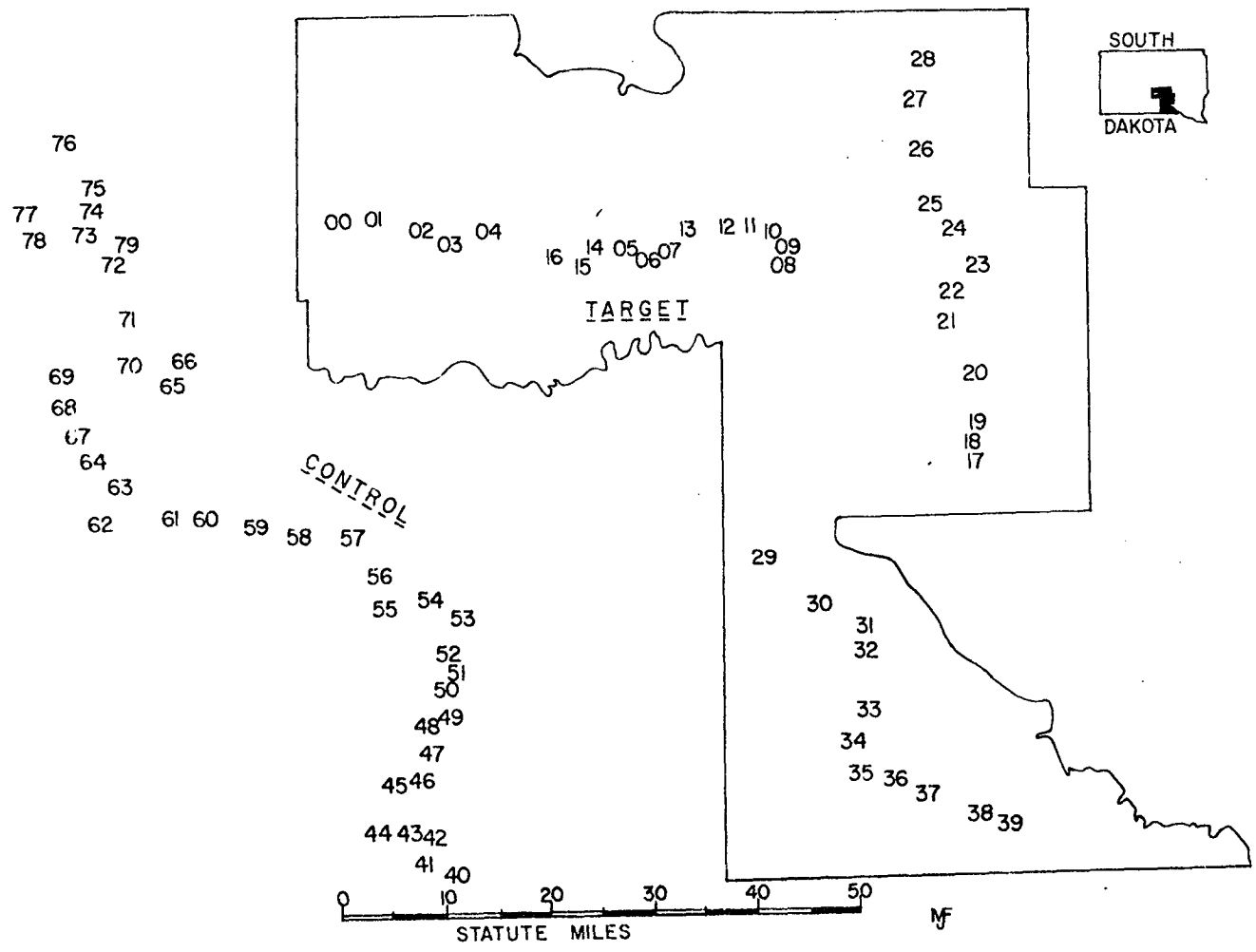

Fig. 2 Map of target and control area stations used for the Brule, Buffalo, Gregory, and Lyman counties target area, 15 May - 15 August 1971. Location of target in state is shown as inset.

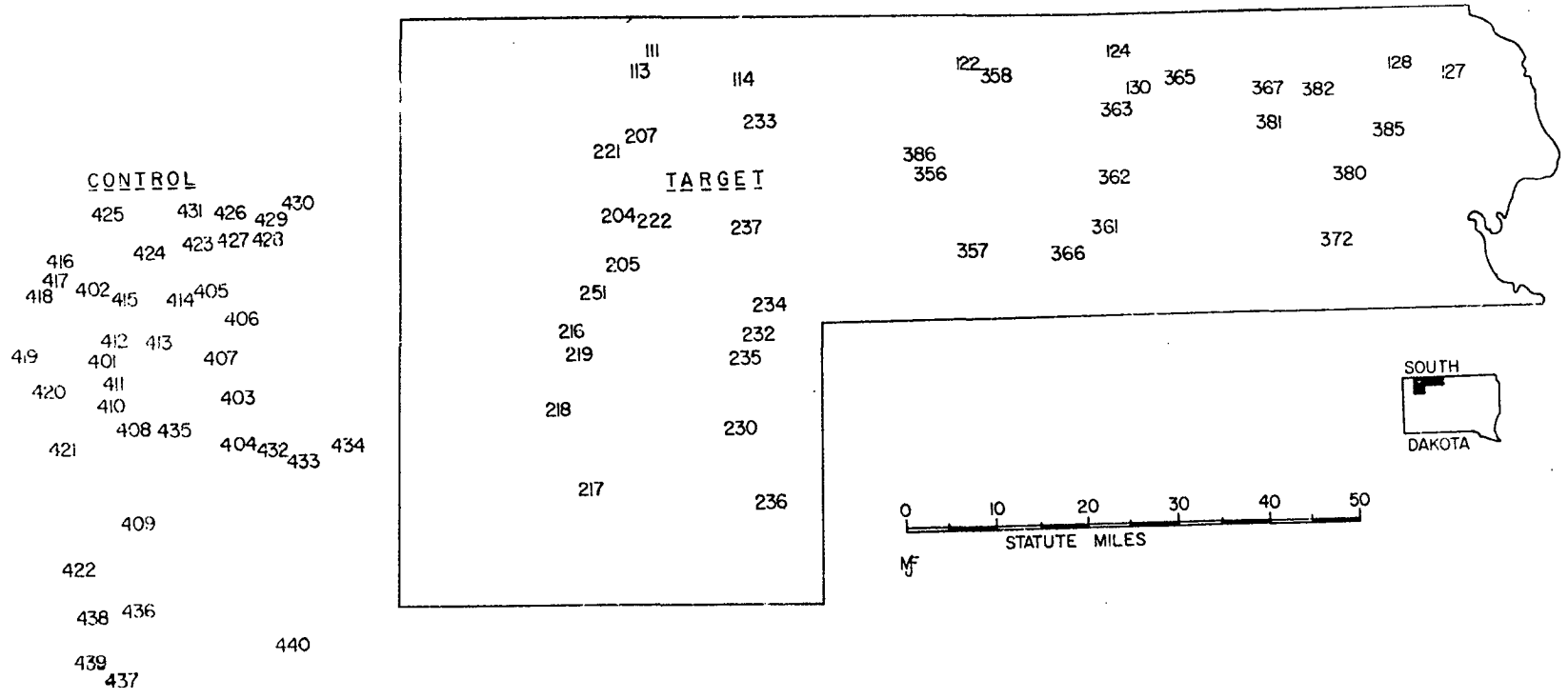

Fig. 3. Map of target and control area stations used for Corson and Perkins counties target area, 15 May - 15 August 1971. Location of target in state is shown as inset.

2. CONTROL AREA SELECTION

A high correlation usually exists between the climates of nearby stations with the correlation decreasing as the distance between the stations increases (Court,1968). For this reason, it is important to select control areas near to targets. It is also important that control areas be free of seeding effects. Since it is conceivable that cloud seeding in a target might increase the precipitation in a downwind control, upwind controls are generally favored. However, since the upwind control for the Grand River Project area could have been affected at times by cloud seeding to the north in Bowman County, North Dakota, a downwind control was used for one investigation (Fig. 1).

There is a reason to suspect that the increased convection stimulated by silver iodide seeding of a large storm may cause increased subsidence for tens of miles surrounding it, thereby suppressing precipitation in nearby parts of target and control areas (Dennis and Schock, 1971). Therefore, it is desirable for control areas to be far enough away from target areas to be free of dynamic effects.

Since a control area cannot be near enough to a target for maximum correlation in climate without running the chance of being influenced by the cloud seeding, the control areas selected for this study are considered to be a compromise. Upwind and downwind controls were arbitrarily selected to be at least 20 miles and 50 miles respectively from the target at the nearest point as measured between the precipitation reporting stations making up these areas.

3. DATA COLLECTION

a. Grand River Project and the Western South Dakota Rain Increase Corporation (WASDRI) Project

Rainfall data were obtained from Climatological Data (U.S. Department of Commerce, NOAA). Only stations (Fig. 1) providing observations from the beginning of the period on which normals were based through the end of the cloud seeding period being investigated were used.

Adequate hailfall data were not available for hail studies for these two projects.

b. Other Projects

Using funds provided by the State of South Dakota, special rain gage and hail indicator networks were installed in target and control areas by the Institute of Atmospheric Sciences (IAS). Cooperative observers

maintained the instruments and provided information in accordance with written instructions.

In 1970 Tru-Chek rain gages and hail indicators were installed at the residences of 27 cooperative observers in the Gregory County target area and at 11 residences in the Tripp County control area (Boyd, 1970).

In 1971 data were collected to evaluate two large cloud seeding projects:

1) A Tru-Chek rain gage and a hail indicator were installed at 40 locations in a target area consisting of Brule, Buffalo, Gregory, and Lyman counties and at 40 locations in a control area in Tripp, Mellette, and Jones counties (Fig. 2).

2) A Forest Service or Tru-Chek rain gage and a hail indicator were installed at 40 locations in a target area in Corson and Perkins counties and at 40 locations in a control area in Harding and Butte counties (Fig. 3).

3) IAS employees visited cooperative observers every two weeks to collect hailfall data, to obtain clarification of any questionable data, and to provide them with any assistance needed.

4. RAINFALL ANALYSES

a. Analysis Procedures

Adjusted target/control ratio (ATCR) computations. The average rainfall measured in targets and in controls for the periods under investigation was used to compute target/control ratios. These target/control ratios were adjusted for normal difference in target and control rainfall by the equation

$$ATCR = \frac{T_s/C_s}{T_n/C_n} ;$$

where ATCR is the adjusted target/control ratio, T_s/C_s is the ratio of the target and control rainfall received during the cloud seeding period, and T_n/C_n is the ratio of target and control normal rainfall.

ATCR's were computed for the months of May, June, July, and August on the WASDRI project, since a seeding responsibility existed for all four months during the 6-year period investigated. Only June and July ATCR's were computed for all other projects, since these are the only full months for which a seeding responsibility existed on all years for all or part of each of the target areas and rainfall normals for less than a full month could not be readily computed from available data.

Rainfall normals. According to Court (1968) shifts in climatic trends may be minimized by computing means (normals) for periods which may be much less than the customary 30 years used by the National Weather Service (NOAA) and others. The optimum base period for normals is believed to be about 15 years. For a particular station it may be different from one month to the next, but tends to be the same for a given month at adjacent stations.

Ideally the base period for normals should not include years in which cloud modification activities, however limited, have been conducted. However, the author was not successful in finding a base period completely free of cloud seeding activities without using a period which included or preceded the dry Dust Bowl years during the 1930's when the climate was considerably different.

Normals for the 15-year period 1950-1964, which had previously been computed for other investigations, were used for all projects except WASDRI (where some seeding had been done on 7 years of the 15-year period.) This eliminated the dry Dust Bowl years, and many stations with climatological records shorter than 30 years could be included. However, these normals cannot be considered to be entirely representative since some light seeding is known to have been done in parts of most target and control areas during the base period, and seeding might have been done in parts of the control areas in Wyoming and Montana unknown to the author. Such seeding could affect the normals and tend to mask seeding effects.

Seeding during the 15-year base period was at a maximum in the Grand River area (Table 1), and the four years on which seeding had been done there were eliminated from normal computations for an additional investigation (Table 2). (The revised normals may still have been affected some by cloud seeding to the northwest in Bowman and Slope counties from 1961 to 1964.)

Normals based on the 1931-1960 period and listed in Climatological Data (U.S. Department of Commerce, NOAA) were used for WASDRI computations since some cloud seeding had been done on a large percentage of the 15-year base period 1950-1964. Thirty-year target area normals were available for only four stations and control area normals were available for only three stations that had been in continuous operation from 1931 through 1970.

Normals based on 1931-1960 data were not used for the other investigations since continuous data for the entire 1931-1970 period were available for only a small number of stations.

In each instance, monthly target and control area normals were computed by averaging the normals for all observational stations used.

b. Grand River Project Area, 1966-1970

Analysis 1. Using an upwind control and normals based on a 15-year period, an ATCR of 1.08 is obtained for the combined months of June and July of the 5-year period (Table 1). This suggests that an 8% increase in June and July rainfall may have resulted from the cloud seeding. As can be expected (Sec. 1) from data collected from only a few observational stations, ATCR's vary greatly from month to month and from year to year.

Analysis 2. Since some light seeding of the Grand River target area had been done on four of the 15 years used to compute the normals for Analysis 1, new normals were computed without using the four seeded years. The results are given in Table 2. The new ATCR's suggest an average increase of 12% in June and July rainfall from the seeding. Since this ATCR is higher than the one found in Analysis 1, it suggests that rainfall was also increased on the four seeded years of the normal period.

Analysis 3. A downwind control was used next for comparison purposes. The ATCR's obtained suggest an average increase in rainfall of about 11% (Table 3). It is not known whether the seeding in the target area influenced the rainfall in the control area. It should be kept in mind, however, that if the rainfall in the downwind control was increased by the cloud seeding, this would reduce the ATCR's and help mask target area seeding effects.

c. WASDRI Area, 1965-1970

Using an upwind control and normals based on a 30-year period, an ATCR of 1.07 is found for the combined months of May, June, July, and August of the 6-year period (Table 4). This suggests that a 7% increase in rainfall for the four months may have resulted from the cloud seeding.

d. Gregory County Project Area, 1970-1971

Using an upwind control in Tripp County and normals based on a 15-year period, an average ATCR of 1.90 is found for the combined months of June and July of the 2-year period (Table 5). This suggests that a 90% increase in rainfall for the two months may have resulted from the cloud seeding. Such a large increase appears to be unrealistically high as compared with the other projects investigated. However, the possibility that higher increases in rainfall have been attained for Gregory County than elsewhere must not be hastily discounted. Higher increases might have resulted from the types of available clouds and seeding techniques used. A contributing factor might be the fact that over one out of four of the seeding flights conducted over the 2-year period were made to seed early morning storms between daylight and 9:55 a.m. (Gregory, Brule, Buffalo, and Lyman counties are the only targets included in this investigation where a large percentage of the storms seeded were of the early morning type.)

e. Brule, Buffalo, Gregory, and Lyman Counties Area, 1971

All four counties of the target area, as well as the three counties of the upwind control area, received below normal rainfall for the combined months of June and July (Table 6). Rainfall varied greatly from place to place with islands of drought existing near areas of relatively high rainfall. However, percent of normal rainfall averaged higher in the target than in the control.

Using normals based on a 15-year period, an ATCR of 1.48 is found for the four-county target area for the combined months of June and July (Table 5). This suggests that a 48% increase in average rainfall for the four-county area may have resulted from the cloud seeding.

f. Corson and Perkins Counties Area, 1971

Below normal rainfall for the combined months of June and July was measured in the target and the upwind control, but the percent of normal rainfall averaged higher in the target than in the control (Table 6).

Using normals based on a 15-year period, an ATCR of 1.08 is found for the combined months of June and July (Table 5).

g. Discussion of Results

On a project basis, the data samples may be too small to support valid conclusions about the effects achieved on rainfall by cloud seeding. However, while target control analyses cannot be readily tested for statistical significance, it appears highly unlikely that the rainfall increases indicated by all seven analyses would have resulted from random variations in natural rainfall. Six of the investigations (Grand River Analyses 3 and 1 or 1: WASDRI area; Dorson and Perkins area; the Brule, Buffalo, Gregory, and Lyman county area; and Gregory County, 1970) appear to be mutually exclusive events. If they are mutually exclusive events, there is only one chance in sixty-four that all six of them would produce apparent rainfall increases due to random variations in natural rainfall.

While the ATCR's collectively support a conclusion that overall rainfall increases have been obtained, the magnitude of these increases should be considered as only approximations. However, the exceptionally large increases indicated for Gregory County over a 2-year period, and for the Brule, Buffalo, Gregory, and Lyman counties area for a 1-year period, suggest that additional investigation is needed to determine whether the large amount of early morning seeding done by the commercial cloud seeding contractor was an important factor.

5. HAILFALL ANALYSES

a. Analysis Procedures

Hailfall data were not available for use in obtaining hailfall normals similar to those used for rainfall (Sec. 4a). Therefore,

another means was used to estimate target/control ratios of normal hailfall for use in adjusting target/control ratios of measured hailfall. Crop-hail loss-cost data (Crop-Hail Insurance Actuarial Association, 1963) for the 1924-1963 period were considered to be proportional to normal hailfall, and these were used to compute normal target/control ratios (NTCR's). Loss-cost is defined as the average crop loss per $100 policy in dollars and cents and is expressed by the equation: Loss-cost = (Losses ÷ Liability) x 100.

Average loss-cost for an area is assumed to be closely related to normal hailfall, even though farming practices and dollar values have changed during the 40-year "normal" period and crop losses may not be exactly proportional to hailfall energy received during the 15 May - 15 August period of cloud seeding (Schleusener and Jennings, 1960). For example, hail losses are influenced by the type of crops grown, their state of maturity, the type of hail, and strength of accompanying winds. Also crop loss will be the same from a hailfall producing 100% crop loss as from a hailfall of much greater intensity.

Crop-Hail Insurance Actuarial Association statistics show that loss-cost values frequently vary considerably from township to township within a county. In light of this, the most detailed loss-cost data available were used in an effort to obtain loss-cost normals representative of actual hail indicator locations within a county.

Average loss-cost values for hail indicator locations in targets and controls were computed by considering the published loss-cost value for a township to be representative of that for all hail indicator locations in it. When the loss-cost for a township was based on less than $100,000 liability, its representativeness was considered questionable and the average loss-cost for adjoining townships was used. Exception: Exceptionally small amounts of crop-hail insurance had been taken in many of the townships in Butte and Harding counties, and it seemed doubtful that the above procedures would obtain representative results. Consequently, the listed county-wide loss-cost averages were used for the control area locations in the two counties.

Adjusted target/control ratios (ATCR's) were computed from the equation

$$ATCR = \frac{T_s/C_s}{NTCR} ;$$

where T_s/C_s is the ratio of the target and control hailfall received during the cloud seeding period and NTCR is the ratio of the average crop-hail loss-cost per station in the target to that in the control during the normal period.

Two years of hailfall data (1970 and 1971) were available for Gregory County and control in Tripp County but, due to budget limitations, hail indicator operations in 1970 could not be monitored closely and the

data obtained were not considered to be of sufficient reliability to merit detailed analysis (Boyd, 1970). Because of this, an analysis is presented only for 1971.

b. Brule, Buffalo, Gregory, and Lyman Counties Area, 1971

Storms were seeded on a 24-hour basis for hail suppression, and it appears that the majority of the target area hail came from seeded storms.

The majority of target and control stations received some hail (Fig. 4). An average of 24 ft-lbs per sq ft of hail energy per station was measured in the target, and 25 ft-lbs per sq ft of hail energy per station was measured in the upwind control in Jones, Mellette, and Tripp counties (Table 7). Using 40-year "normals" (Sec. 5a), an ATCR of .99 is found for the 15 May - 15 August period of seeding.

c. Corson and Perkins Counties Area, 1971

Some hailfall was measured at all control area stations and at all but one target area station (Fig. 5). Some of the target hailfall came from unseeded nighttime storms.

An average of 38 ft-lbs per sq ft of hail energy per station was measured in the target and 55 ft-lbs per sq ft of hail energy per station was measured in the upwind control in Butte and Harding counties (Table 7.) Using 40-year "normals" (Sec. 5a), an ATCR of .94 is found for the 15 May - 15 August period of seeding.

d. Discussion of Results

It is very surprising that one year of hailfall data would yield ATCR's only .05 apart for the two projects and that the ATCR's are so close to one in magnitude.

If nature provided a normal amount of hail opportunities for the targets and their controls, the hail indicator measurements provided a representative sampling of target and control hailfall, and if accurate target/control ratios of normal hailfall were obtained from the crop-hail loss-cost data, it could be concluded from the ATCR's obtained that hailfall was slightly decreased by the seeding.

It appears that the use of crop-hail loss-cost data may be a satisfactory method of determining target/control ratios of normal hailfall. Therefore, with the addition of comprehensive hailfall data for several more seasons, it should be possible to obtain good estimates of the overall effects of the cloud seeding on hailfall in the two target areas.

TABLE 1

Rainfall Analysis 1 for Grand River Cloud Seeding Target Area

Year	JUNE T_s/C_s (in)	JUNE ATCR*	JULY T_s/C_s (in)	JULY ATCR*	JUNE & JULY T_s/C_s (in)	JUNE & JULY ATCR*
1966	3.31/2.37	1.23	3.42/1.83	1.63	6.73/4.20	1.40
1967	4.32/4.71	.80	.53/1.44	.32	4.86/6.15	.69
1968	5.39/4.17	1.14	1.19/1.51	.69	6.58/5.68	1.01
1969	4.10/4.08	.88	4.52/2.11	1.87	8.62/6.19	1.22
1970	2.56/2.05	1.10	1.72/1.02	1.47	4.28/3.07	1.22
Ave.	3.94/3.48	.99	2.28/1.58	1.26	6.22/5.06	1.08

CLOUD SEEDING: Some commerical or experimental seeding with silver iodide was done in the area during June and July and usually the last half of May and the first half of August 1966 through 1970.

NORMALS: Based on 1950 through 1964 period. Target area was lightly seeded with ground generators in 1951, 1952, and 1953, and by an airplane in 1962, which could affect the normals and mask seeding effects during the period under investigation.

TARGET AREA STATIONS: Bison, Shadehill Dam, Lemmon, Usta, McIntosh, and McLaughlin (Fig. 1).

CONTROL AREA STATIONS: Belle Fourche, Redig, Camp Crook, Albion, Ridgway, and Ekalaka. Control area is centered about 120 miles upwind from the center of the target area (Fig. 1).

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*Where T_n/C_n (Sec. 4a) is 3.18/2.79 for June, 2.14/1.87 for July, and 5.32/4.66 for the two-month period.

TABLE 2

Rainfall Analysis 2 for Grand River Cloud Seeding Target Area

Year	JUNE T_s/C_s (in)	ATCR*	JULY T_s/C_s (in)	ATCR*	JUNE & JULY T_s/C_s (in)	ATCR*
1966	3.31/2.37	1.41	3.42/1.83	1.46	6.73/4.20	1.46
1967	4.23/4.71	.91	.53/1.44	.29	4.86/6.15	.72
1968	5.39/4.17	1.31	1.19/1.51	.61	6.58/5.68	1.06
1969	4.10/4.08	1.02	4.52/2.11	1.67	8.62/6.19	1.27
1970	2.56/2.05	1.26	1.72/1.02	1.32	4.28/3.07	1.29
Ave.	3.94/3.48	1.14	2.28/1.58	1.13	6.22/5.06	1.12

CLOUD SEEDING: Some commerical or experimental seeding with silver iodide was done in the area during June and July and usually the last half of May and the first half of August 1966 through 1970.

NORMALS: Based on 1954 through 1961, 1963, and 1964. It is believed that no seeding was done during any of these years.

TARGET AREA STATIONS: Bison, Shadehill Dam, Lemmon, Usta, McIntosh, and McLaughlin (Fig. 1).

CONTROL AREA STATIONS: Belle Fourche, Redig, Camp Crook, Albion, Ridgway, and Ekalaka. Control area is centered about 120 miles upwind from the center of the target area (Fig. 1).

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*Where T_n/C_n (Sec. 4a) is 3.02/3.05 for June, 2.27/1.77 for July, and 5.29/4.82 for the two-month period.

TABLE 3

Rainfall Analysis 3 for Grand River Cloud Seeding Target Area

Year	JUNE T_s/C_s (in)	JUNE ATCR*	JULY T_s/C_s (in)	JULY ATCR*	JUNE & JULY T_s/C_s (in)	JUNE & JULY ATCR*
1966	3.31/1.91	2.09	3.42/3.14	1.30	6.73/5.05	1.60
1967	4.32/5.50	.95	.53/1.20	.53	4.85/6.38	.91
1968	5.39/5.59	1.16	1.19/2.36	.60	6.58/7.95	.99
1969	4.10/4.23	1.17	4.52/4.43	1.22	8.62/8.66	1.19
1970	2.56/3.14	.98	1.72/1.97	1.04	4.28/5.11	1.00+
Ave.	3.94/4.07	1.17	2.28/2.62	1.04	6.24/6.69	1.11

CLOUD SEEDING: Some commerical or experimental seeding with silver iodide was done in the area during June and July and usually the last half of May and the first half of August 1966 through 1970.

NORMALS: Based on 1950 through 1964 period. Target area was lightly seeded with ground generators in 1951, 1952, and 1953, and by aircraft in 1962, which could affect the normals and mask seeding effects during the period under investigation.

TARGET AREA STATIONS: Bison, Shadehill Dam, Lemmon, Usta, McIntosh, and McLaughlin. (See Fig. 1).

CONTROL AREA STATIONS: Bowdle, Eureka, Ipswich, Leola, Roscoe, and Ashley. Control area is centered about 130 miles downwind from the center of the target area. (See Fig. 1).

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*Where T_n/C_n (Sec. 4a) is 3.18/3.83 for June, 2.14/2.55 for July, and 5.32/6.38 for the two-month period.

TABLE 4

Rainfall Analysis for WASDRI Cloud Seeding Target Area

Year	MAY T_s/C_s (in)	MAY ATCR*	JUNE T_s/C_s (in)	JUNE ATCR*	JULY T_s/C_s (in)	JULY ATCR*	AUGUST T_s/C_s (in)	AUGUST ATCR*	MAY-AUGUST T_s/C_s (in)	MAY-AUGUST ATCR*
1965	7.03/3.81	1.41	3.78/3.82	.75	1.67/2.29	.58	1.49/ .52	2.27	13.97/10.44	1.03
1966	.23/ .19	.93	1.21/ .96	.95	4.39/2.56	1.35	2.80/2.59	.86	8.63/ 6.30	1.06
1967	3.37/1.98	1.31	6.88/4.06	1.28	1.35/1.30	.82	1.21/ .68	1.41	12.81/ 8.02	1.23
1968	2.22/2.59	.66	6.01/3.93	1.15	3.54/ .53	5.28	2.78/1.92	1.15	14.55/ 8.97	1.25
1969	2.14/1.21	1.36	2.50/3.47	.54	4.80/3.09	1.23	.83/ .14	4.69	10.27/ 7.91	1.00+
1970	2.36/3.40	.53	2.51/1.50	1.26	1.71/1.96	.69	1.00/ .23	3.44	7.58/ 7.09	.83
Ave.	2.89/2.20	1.01	3.81/2.96	.97	2.91/1.95	1.18	1.68/1.01	1.32	11.30/ 8.12	1.07

CLOUD SEEDING: Some commerical seeding with silver iodide was done in the target during May-August period; however, from about 1 June to 15 August, commerical seeding was limited to weekends and holidays in about one-half of area due to experimental seeding on weekdays by the Institute.

NORMALS: Based on 1931 through 1960 period. Target area seeded lightly with ground generators in 1951, 1952, and 1953, which may have had some effect on the normals and may slightly mask seeding effects during the period under investigation.

TARGET AREA STATIONS: Rapid City, Rapid City WB, Custer, and Hot Springs (See Fig. 1).

CONTROL AREA STATIONS USED: Newcastle, Rochelle, and Dull Center, Wyoming. Control area is centered about 70 miles upwind from the center of the target area. (See Fig. 1).

*Where T_n/C_n (Sec. 4a) is 2.92/2.24 for May, 3.14/2.37 for June, 1.95/1.54 for July, 1.68/1.33 for August, and 9.67/7.48 for the four-month period.

TABLE 5

Rainfall Analyses for Cloud Seeding Projects of 1 to 2 Years' Duration

Area	Year	JUNE T_s/C_s*	JUNE T_n/C_n*	JUNE ATCR	JULY T_s/C_s*	JULY T_n/C_n*	JULY ACTR	JUNE & JULY T_s/C_s*	JUNE & JULY T_n/C_n*	JUNE & JULY ATCR
Gregory Co.	1970			1.91**			1.01**			1.46**
	1971	1.70/1.22	4.01/3.78	1.31	3.87/1.00	2.89/2.67	3.56	5.57/2.22	6.90/6.45	2.34
	Ave			1.61			2.28			1.90
Brule, Buffalo, Gregory, & Lyman Counties	1971	1.61/1.67	3.48/3.69	1.02	2.22/ .90	2.59/2.36	2.25	3.82/2.57	3.04/3.02	1.48
Corson & Perkins Counties	1971	3.05/3.97	3.23/2.93	.70	1.93/ .25	1.99/1.83	7.23	4.98/4.22	5.22/4.76	1.08

CLOUD SEEDING: Commercial cloud seeding with silver iodide was done from 15 May through 15 August in each county during 1971. Gregory County was seeded in 1970 also.

NORMALS: Based on 1950-1964 period. Some light seeding in Corson, Perkins, Jones, and Lyman counties during the 1951 to 1953 period and in 1962 in Corson and Perkins counties may have affected the normals.

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* Average rainfall per station in inches.

**From Report 70-14, Rain and Hailfall Analyses for Gregory County Cloud Seeding Project (1970) (Boyd, 1970).

TABLE 6

Rainfall Received in 1971 in Target and Control Area Counties

COUNTY	NORMAL*(IN)	JUNE & JULY (IN)	PERCENT OF NORMAL
Brule & Buffalo**	6.28	3.11	49
Gregory	6.90	5.57	81
Lyman	5.40	3.04	56
Jones	5.55	2.53	46
Mellette	5.89	3.05	52
Tripp	6.45	2.22	34
Corson	5.36	5.26	98
Perkins	5.08	4.71	93
Harding & Butte**	4.76	4.22	89

*Average for stations based on actual rain gage locations.

**Two counties combined because of small number of gages in one of them.

TABLE 7

Hailfall Analyses for Cloud Seeding Projects Conducted 15 May - 15 August 1971

AREA	AVERAGE HAIL ENERGY PER STATION (ft-lbs/ft^2)	T_s/C_s* (ft-lbs/ft^2)	NTCR*	ATCR*
Brule & Buffalo Co.	14			
Gregory Co.	15			
Lyman Co.	40			
ENTIRE TARGET	24	24.31/24.60	4.97/4.98	.99
Jones Co.	36			
Mellette Co.	35			
Tripp Co.	10			
ENTIRE CONTROL	25			
Corson Co.	21			
Perkins Co.	55			
ENTIRE TARGET	38	38.01/55.46	7.27/10.01	.94
Butte and Harding Co. Control	55			

*See definitions in Sec. 5a.

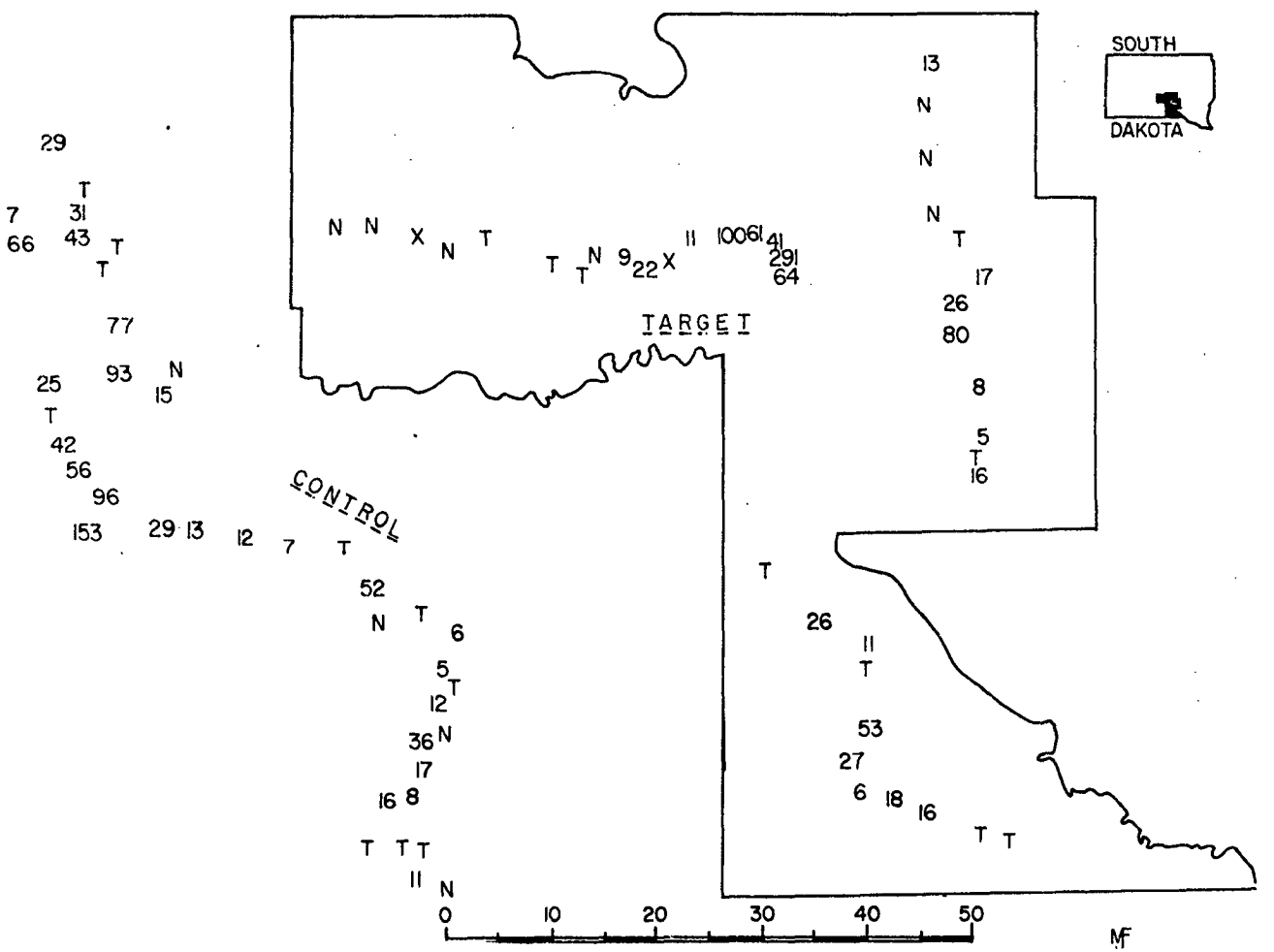

Fig. 4. Hailfall energy (ft-lbs per sq ft) for observing stations in target and in the control, 15 May - 15 August 1971. A "T" shows total hailfall energy of less than 5 ft-lbs per sq ft. An "N" indicates that hail was not observed by the station, and an "X" indicates that data were not obtained from an installed hail indicator.

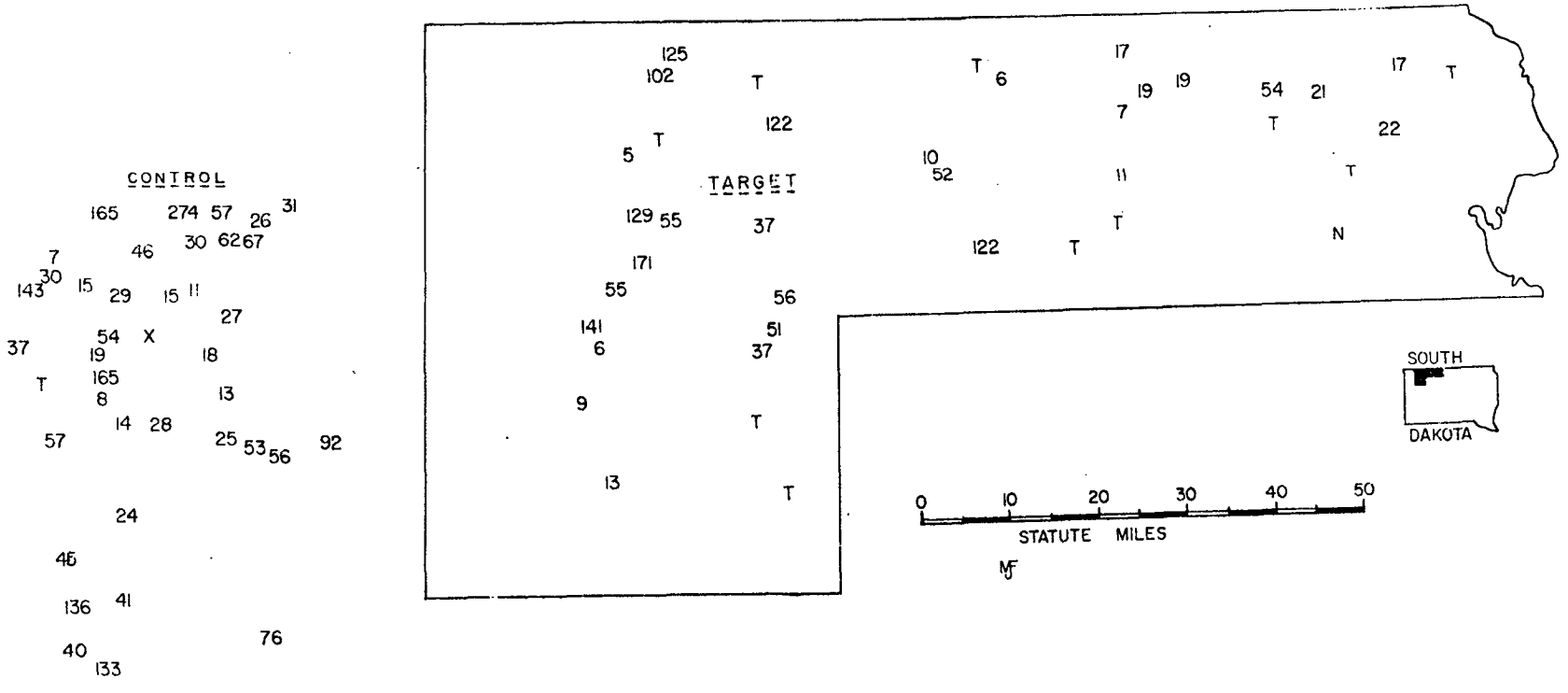

Fig. 5. Hailfall energy (ft-lbs per sq ft) for observing stations in the target and in the control 15 May - 15 August 1971. A "T" shows hailfall energy of less than 5 ft-lbs per sq ft. An "N" indicates that hail was not observed by the station, and an "X" indicates that data were not obtained from an installed hail indicator.

6. CONCLUSIONS AND RECOMMENDATIONS

Target/control ratios, adjusted for normal differences in target and control rainfall, show that rainfall received over seven cloud seeding targets was from 7 to 90% more than could be expected by comparison to rainfall over the controls. This indicates that rainfall over the targets was increased by the cloud seeding.

There are indications that cloud seeding yields a higher percentage of increased rainfall in the south-central part of the state than in the western. This could be because a relatively large number of storms seeded in the south-central part of the state have been of the early morning type. Therefore, future research should be oriented (1) to determine whether early morning storms respond especially well to seeding for increased rainfall and (2) to perfect the cloud seeding technology for increasing spring and summer rainfall in South Dakota.

Target/control ratios, adjusted for normal difference in target and control hailfall, indicate that hailfall received over two cloud seeding targets was from 1 to 6% less than could be expected by comparison to hailfall over the controls. Since the target/control ratios are based on data for only one season, an adequate basis does not exist for drawing any conclusions about the effects of the cloud seeding on hailfall. Therefore, the collection of hailfall data should be continued for use in evaluating the effects being obtained by cloud seeding. In the meantime, research should be accelerated (1) to model hailstorms, so that all major inflow areas can be readily located by cloud seeders, and (2) to develop the best possible cloud seeding technology for hail suppression purposes.

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Marion N. Bruce, South Dakota Weather Control Commission, had earlier obtained similar results to those reported herein from informal rainfall studies for some of the same target areas using somewhat different control areas and base periods for normals.

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AN EXPERIMENT IN COMPUTER ASSISTED DECISION MAKING FOR WEATHER MODIFICATION

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INTRODUCTION - DECISION MAKING AND WEATHER MODIFICATION

From the introduction of the computer to meteorology some twenty years ago (Klein,1969) to the present there has been, as in all of science, a remarkable growth in the use of the computer and its many products. The rapid advancement of computer technology itself has made possible the solutions to problems of ever-increasing complexity.

Perhaps the greatest application of computers by meteorologists has been in the area of numerical weather prediction. The use of numerical models for predictive purposes, first applied to synoptic scale fields of motion, has been extended so that today there exist models which describe meteorological phenomena on nearly every scale from the global to the micro. This use of numerical models to describe and predict has become so widespread that it has tended to overshadow all other types of models and applications.

Kreitzberg (1969) has defined four catagories of models which are used in meteorology: descriptive, dynamic, numerical and statistical. Models have application for education, research, or operations. Any user must carefully choose the right type of model to fit the desired application. This may mean that the user finds it profitable to select a relatively simple model in the place of a more complex one. It is the desired end result and not the model itself which determines the choice.

Although models corresponding to all four categories have been used in weather modification, this use has been limited primarily to research applications. There have been from time some applications of modeling in the area of operations but this has been limited to the solution of rather specific problems. For example models have been used to predict the heights of rising cumulus towers but have not been used to determine whether or not such towers will actually occur on a given day.

The use of models for weather modification operations implies the field usage of computer and until recently computers have been inaccessible to field operators and the products inappropriate. The reasons for this have been documented by Peterman (1970) but it can be simply stated that there has been a distinct lack of effort directed towards the development of a system containing both data and models for operational use in weather modification.

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Since it is generally impossible to physically bring together field operators and computer facilities it is necessary to provide a means for remote computer access. Time-sharing employing inexpensive, portable teletype computer terminals provides the most appropriate framework for remote computer use. Recent time-sharing software advances have made it possible to perform nearly any type of computations which can be done in "batch" processing. The only restriction to time-sharing is in output. However this limitation is not critical for operational use where short, precise outputs are desired.

Using the time-sharing concept as the basic framework, along with an assessment of the product requirements for weather modification operations a system of computer programs and models was developed for use in the Bureau of Reclamation, Project Skywater program. Beginning as a crude idea and developing through a series of experiments (Cohen, 1970) this system was placed into operational status in November 1970. This paper briefly discusses the original system configuration and then describes a major experiment designed to test the usefulness of computer assisted decision making in weather modification. Out of this experiment conducted at Flagstaff, Arizona during July and August, 1970 the decision was made to place the time-sharing decision system into an operational status.

CONFIGURATION OF THE TIME-SHARING SYSTEM

Kreitzberg (1969) discusses the need for an interactive forecasting system designed to make optimal usage of both the computer's computational efficiencies and of man's creative abilities. The system described in this paper can be considered as the first step towards such a system. Data, programs, and models, pertinent to weather modification operations are stored within the computer. The forecaster, decision maker, chooses the combination of these three which best meets his needs and by conversing with the computer in a "question and answer" mode develops his analysis which leads to the forecast. The system is therefore flexible since within the limitations of data and products the decision maker can select any procedure by which to develop the forecast.

For the July-August, 1970 experiment the data base consisted of the current upper air soundings for the western United States. Man-power limitations restricted the data to the 1200 GMT observations only. The data were received and processed at the Division of Atmospheric Water Resources Management (DAWRM) office in Denver, Colorado and were then stored in the time-share memory. The time-sharing network used for the experiment was the General Electric MARK II system. The MARK II processor was located in Los Angeles, California.

Analyses programs and models stored within computer memory were as follows:

1. Pennsylvania State University (PSU) Steady State Cumulus Model. This is the well known one dimensional cloud model developed by Weinstein and Davis (1968).

2. Program MESOMOD. This is a variation of the PSU model developed by C.W. Kreitzberg and D. Perkey. It describes the successive growth of cumulus towers and resultant environmental modification.

3. Program Sounding Analysis. This is a program developed by the author which yields a complete analysis of a single upper air observation.

4. Program Cross Section. This is a program developed by the author used to generate cross-sectional slices for a variety of atmospheric parameters and routes.

5. Program Constant Pressure Chart. This is a program developed by the author which produces a isobaric chart for a number of parameters at any desired pressure level.

Each program and model operates in a conversational mode. The user at the remote teletype terminal indicates which program or model is desired and then by proceeding through a short question and answer routine specifies the exact analyses wanted. For example it would be possible with the system to obtain a 550 mb pressure chart with dewpoint as the plotted parameter. An example of the question and answer routine for the Constant Pressure Chart program is shown in Figure 1.

OPERATION OF THE TIME SHARING SYSTEM

The experiment was conducted from 20 July to 8 August 1970 in conjunction with a series of cumulus seeding tests being performed by Meteorology Research Incorporated (MRI), Altadena California. The purpose of the experiment was twofold. There was the need first to test the mechanics of the time-sharing system configuration and second, to determine the value of such a system to a weather modification operation.

Field operations for the experiment were coordinated at the Flagstaff airport from a small camper-type trailer in which the remote computer terminal along with the peripheral analysis equipment were located. The trailer also served as the coordination center for the overall cumulus seeding experiment. A schematic diagram showing the complete configuration of the time-sharing system is given in Figure 2.

University of Denver staff (the author and an assistant) would arrive at the field site at approximately 0645 MST each experimental day and begin using the time-sharing system to prepare an initial forecast presented at an 0830 MST briefing. Both local data entered from the remote terminal and data being entered into the system from Denver were used to prepare the forecast. At the briefing, based upon the time share analysis, an initial decision was made regarding the days operation by MRI. Following the briefing the time-share system would be used to refine and update all weather information. Local sounding observations were analyzed and horizontal and cross-section charts were generated in an attempt to improve upon the initial forecast. Through this continual updating it was possible to provide the MRI decision makers with the most accurate, timely forecast. Such a flexible procedure allowed for an alteration of the experimental plan at any time during the day's operation.

The meteorological predictions that must be made during a summertime cumulus experiment are as follows: (1) will there be cumulus development and, if so, when will it begin, when will development be at the maximum, what will the cloud sizes be, how many clouds of each size will there be and what will be their geographical distribution; (2) from the population of expected clouds which sizes will be the best for modification and what will be the best time to attempt seeding; (3) will convection be organized and/or will seeding lead to a greater degree of organization; (4) what are the longer range possibilities for cloud development during the next one or two days? It was for the purpose of attempting to provide precise and accurate answers to these questions that the test of the time sharing system was conducted.

As has been discussed by Weinstein (1971) the steady state convection model is an important predictive tool for use in cumulus modification experiments. Output from this model was used to construct an "envelope" of possible potential convection. By running the model for various probable cloud bases it was possible to determine the limits of probable convection for the given atmospheric structure of moisture and stability. Small changes in cloud base height or radius are often critical factors determining whether convection will be suppressed or not. Through the development of such an envelope it was possible to begin the construction of a time scale for convective events for the day in question. The PSU model was run for all Winslow Arizona (INW) and locally taken Flagstaff upper air observations.

The successive growth cumulus model was found to be a useful supplement to the steady state model and was run daily in conjunction with it. Use was made of its output to further elucidate the probable timing of cumulus activity for the given day.

The sounding analysis, cross-section, and constant pressure chart programs were used to construct a three-dimensional image of the atmosphere. Sounding analyses for Flagstaff and for nearby upper air stations were used to study the detailed vertical distribution of such key atmospheric parameters as stability and moisture. Based upon the sounding analyses, levels were chosen for which to generate constant pressure charts. Since any pressure level can be constructed it was possible to study moist and dry regions at their maximums and thus to obtain a clearer understanding of any potential moisture advection. Finally selected cross-sections were generated. Cross-sections of equivalent potential or moist potential temperatures were used to detect subtle changes in stability patterns while displays of relative humidity were used to further clarify the three-dimensional moisture patterns.

After generating all three of the above analyses, it was often possible to construct a predicted sounding for the Flagstaff area. This prediction, based upon flow patterns, moisture and stability advection and other factors would then be used as input to the PSU steady state model to generate a new predicted modification potential. This new prediction would then be used to update and revise when necessary, the initial operational decision. This feedback from analyses to models was found to be an important aspect of the operation of the time-sharing system.

RESULTS AND CONCLUSIONS

The time-sharing system was operated each experimental day from 20 July to 8 August and forecasts leading to operational decisions were prepared. In all some 219 individual computer products were generated along with hand drawn maps, numerous visual cloud observations and data from a mobile weather unit supplied by the Bureau of Reclamation. The data were carefully recorded and summarized for post experiment analysis of the value of the time-sharing system. Although it is not possible in this paper to discuss the activities for each day, interested readers are referred to a technical note by Weder and Peterman (1970) in which is presented for each day a detailed description of the decision making activities, the weather sequence and a subjective evaluation of the forecasted weather versus actual weather.

Since the purpose of the experiment was to test and evaluate the use of a system intended to provide weather modification decision makers with continuously updated, revised weather information for use in short term (possibly only minutes) forecasting it is difficult to objectively determine its accuracy. Since in such a system no forecast is considered permanent and is continually being updated and improved it is hardly appropriate to judge the forecast quality at any given point of the forecast process.

Also forecasts which did result from the operation of the system attempted to predict the total cloud and precipitation development for the experimental day, including cloud distribution, maximum heights, rainfall intensity, timing of cloud cycles, and changes which might result from any modification attempted. It seems unlikely that any objective scheme could be used to evaluate such a detailed forecast.

None-the-less it did seem desirable to obtain at least a general measure of how well the system performed. Therefore an independently conducted, subjective evaluation was performed which attempted to draw from the data for each day an evaluation of the system. Resulting from this evaluation was the conclusion that out of the fifteen days which could be evaluated only two forecasts were incorrect. Of the remaining thirteen days eight forecasts were perfect or near perfect while five were essentially correct on all of the forecast factors expect one.[1]

More important than the subjective evaluation was the conclusion by all of those who participated in the experiment that the use of the time-sharing system had improved the weather modification operations. Although some definite flaws and limitations in the system were noted it was felt that the test had been a success and that future weather modification experiments would indeed benefit through the utilization of such a system.

Major defects in the system were two. The first was mechanical and related to the processing of the upper air data. The decoding and storing procedure

[1]For example cloud heights, amounts and geographical distribution may have been correctly predicted but the timing of convective occurrences was missed.

conducted at the Bureau of Reclamation Office in Denver was at best time-consuming and frustrating and often delayed the availability of the data at the Flagstaff site.

Second, a more flexible system would have been desirable. This could be best accomplished by increasing the number of programs and models available with the system and developing improved output products.

Following the Flagstaff experiment, it was the decision of the Division of Atmospheric Water Resources Management, Bureau of Reclamation to implement the time-sharing system on an operational basis available to all of their field operations beginning with the 1970-71 wintertime seeding season. The precedure for acquiring, decoding and storing data was automated, each system program and model was updated and work was begun on several new programs for the system. The system began daily 24 hour operation during November 1970 and after an initial introductory period operated smoothly. During the spring and summer of 1971 several additions and improvements in the system were made further increasing its usefulness.

Thus from the 1970 Flagstaff experiment, which followed from a period of extensive research into the use of computer systems and the information needs of weather modification operators has come the growth and development of a unique system for meteorological decision making. This system utilizing both human creativity and computer speed represents an attempt to provide specific information for the solution of user-oriented problems. Hopefully the results of the Flagstaff experiment can be applied to other areas of meteorology where similar specific answers must be obtained from a diverse set of data and analyses routines.

ACKNOWLEDGEMENTS

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 ENTER ALL STATIØN CØDES IN ØRDER
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 BUREAU ØF RECLAMATIØN
      DIVISIØN ØF ATMØSPHERIC WATER RESØURCES MANAGEMENT
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Figure 1. An Example of the Question and Answer Routine Required to Generate an Analysis with the Time-Sharing System. (user responses are underlined).

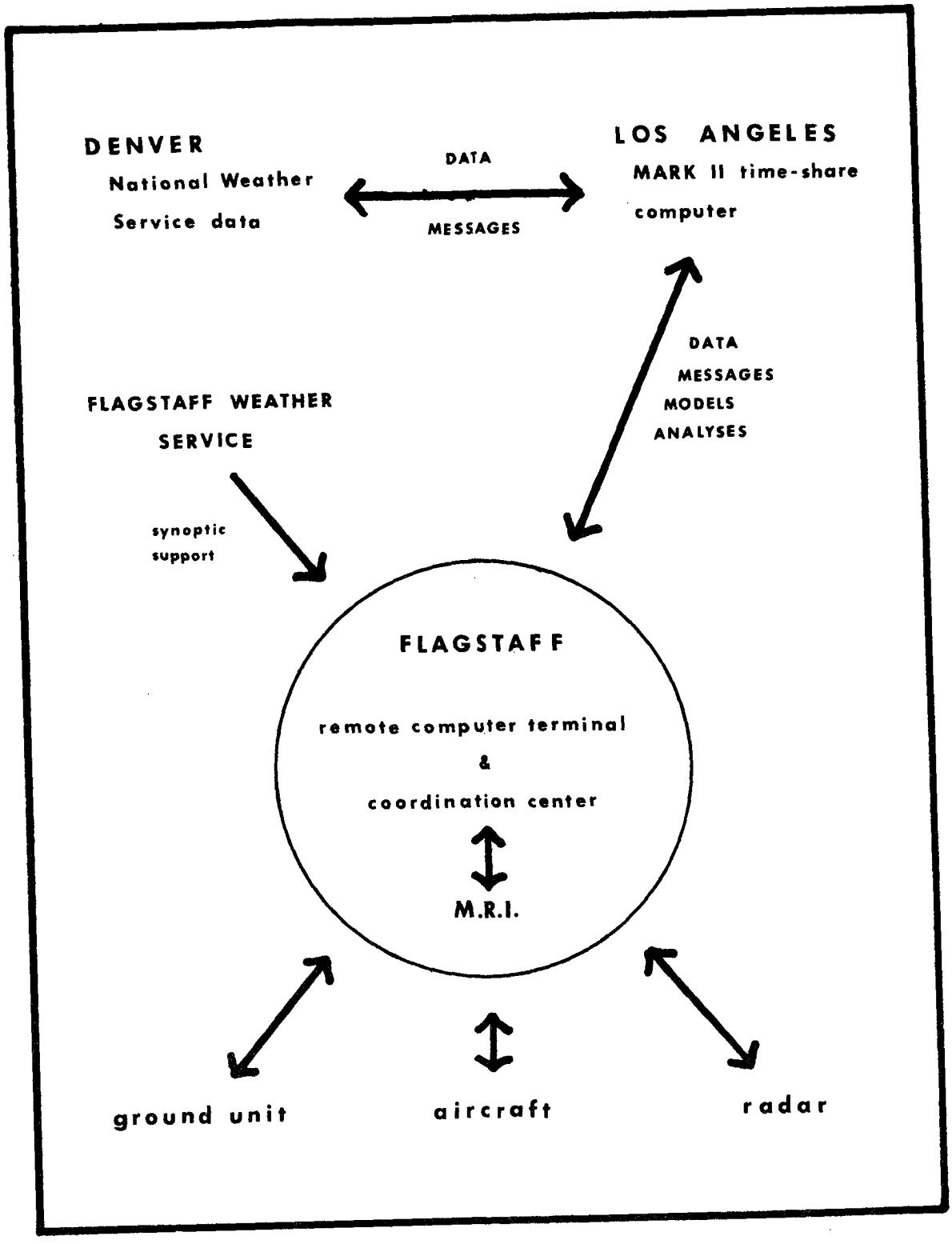

Figure 2. A Schematic Diagram of the 1970 Flagstaff Experiment Time-Sharing System.

SOME RELATIONSHIPS TO WEATHER MODIFICATION

OF FINE PARTICLES IN THE ATMOSPHERE

by

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The question of inadvertent weather modification [1] is receiving increased attention by the general public as well as the scientific community. This has recently resulted in the initiation of a major field study in the vicinity of St. Louis, Missouri. [2]

FINE PARTICLES IN THE ATMOSPHERE

There is still much uncertainty about this subject and a considerable amount of misunderstanding about some of the basic principles which are an inherent part of the present problem.

This can be described by two words - "small particles," or, as the Environmental Protection Agency now prefers to call them, "fine particles." These are particles of many types, origins and combinations having cross sections less than one micron (10^{-4} cm) (10^{-6} micrometers) (1/25,000 in.). The lower limit of fine particles is in the range of 0.002 microns (2×10^{-7} cm). I prefer to consider the dividing line between the larger aerosols and fine particles at 0.6 microns (6×10^{-5} cm) in average cross section. This is the diameter of liquid droplets that are most efficient in the scattering of visible light since they have a cross section equivalent to the visible yellow region of the solar spectrum. It was this size of particle that we used during World War II for providing smoke screens. [3] Thousands of smoke generators patterned after the so-called Schaefer-Langmuir Smoke Generator were utilized for the crossing of the Rhine, for hiding the Anzio beachhead, in the North Africa campaign and to protect planes from kamikaze attacks in the South Pacific. Of course, the advent of radar and infrared sensors virtually eliminated the value of fine particle smokes for screening purposes. Incidentally, the studies in our smoke test chamber at the G.E. Research Laboratory clearly showed that 0.6 micron diameter smoke was of no value whatsoever in protecting orchards from frost, since the loss of infrared radiation from the earth is not affected by fine particles even though they are highly effective in the scattering of visible light. To be

effective as a screening layer in the infrared range, the particles must be the size of small cloud droplets having a cross section of about 10 microns.

RELATIONSHIP OF FINE PARTICLES TO MOISTURE

In order to determine whether or not fine particles from anthropogenic as well as natural sources play a role in weather and climate modification, it is essential that their concentration and size be established in three-dimensional configurations. It is also necessary to determine the size distribution of these particles, and, in particular, the relative numbers of all particles which can grow rapidly when moisture is present. Thus, it is important that determinations be made of the potential for growth and activity of cloud condensation nuclei at relative humidities above 70% up to a water supersaturation of about 1%, and of ice nuclei at all supersaturations with respect to ice at temperatures colder than 0° C. These are the parameters which cause fine particles to grow rapidly.

THE INCREASE IN NUMBER OF FINE PARTICLES

Despite a massive effort on the part of Federal and State agencies to reduce air pollution on the local, regional and continental scale, the problem of air pollution is becoming more severe.* In some areas where previously the air has been very clean (<1000/cc), the measurement of small particles in the atmosphere now shows values ten times higher than was the case ten years ago.[1]

Thus, the United States is presently confronted with a worsening and more widespread air quality deterioration at present despite evidence that at monitoring sites in the cities there is strong evidence of lowering values. Why is this? It is likely that the monitoring stations have not been measuring all of the critical parameters related to air quality.

Air particulate measurements that are made by our national Environmental Protection Agency network depend on the values recorded by the high volume sampler. This is a device which passes a large volume of the ambient air through a glass fiber filter. After a specified period of time, this filter is weighed and the particulate level is then given as micrograms per cubic meter of airborne particles that have been gathered by the filter.

SOME FACTORS CONTROLLING THE QUALITY OF AIR

The quality of air depends on three major items. The first of these is the weight of airborne material; the second is the chemical and physical

* On Nov. 16-19, 1971, the first order ever made to curtail industrial activities was issued by the Environmental Protection Agency due to severe smog over most of the Eastern Seaboard, centered at Birmingham, Alabama.

composition of the suspended material; and the third is the number of the suspended particles. The high volume sampler measures the first of these- i.e., the weight. The collected residue can also be analyzed for physical and chemical properties to provide information about the second factor. The high volume sampler does not and cannot measure the third factor, i.e., the number of particles.

One large particle having a diameter of 100 microns, 0.004", which is barely visible to the naked eye, can cause pain if it lands in one's eye on a windy day. (Such a particle has a cross section about equivalent to that of the diameter of a human hair.) However, if such a particle were vaporized and condensed to form smaller ones having a cross section of 0.5 microns, this one large particle will produce nearly ten million of the smaller ones. A particle of this smaller size is not only more visible by the light it scatters, but it has a much longer residence time in the atmosphere and causes a considerably greater reduction in visibility and is a more serious health hazard since it will pass through the upper respiratory tract and quite likely will be deposited in the lungs.

Thus, it is extremely important that we learn more about this important aspect of the air pollution problem to better inform the general public as well as the control and monitoring agencies. With a better understanding of this aspect of the problem and its spatial dimensions, action can then be taken to control sources of such fine particles and to better understand the manner in which they are removed from the atmosphere.

SOURCES OF FINE PARTICLES

The sources of fine particles are the exhaust pipes of automobiles, motor boats and all other internal combustion engines, the effluents of industry, especially those having what appear to be plume-free chimneys, incinerators, central heating in the home and other places, the fossil fuel burning power plants and a number of natural sources. However, except for volcanic eruptions and forest fires, the concentration of fine particles from nautral sources on the continental and even global scale rarely produces more than 1000 of the fine particles per cubic centimeter having a size less than 0.6 microns in cross section. On the other hand, the concentration of such particles that can be traced to anthropogenic sources ranges from 1000 to more than 50,000 particles per cc.

Thus, as the visiblity in the air of the lower atmosphere is impaired it is of great national importance that the general public, and especially those who are charged with controlling this problem, become better informed about the sources and the problems caused by small particles.

THE SPREAD OF FINE PARTICLE PLUMES

To an ever-increasing degree, the spread of small particle pollution is permeating the troposphere. To those who fly cross-country in aircraft, this is a development that is quite obvious. Reduced visibility of the ground and distant objects is of very frequent occurrence.

One can fly from Los Angeles and commonly observe pollution plumes from the West Coast extending to Phoenix, Las Vegas and even farther to the northeast. It is a common experience to encounter reduced visibility from Boston to New Orleans and New York to Chicago and even Denver. Such plumes extend over the Atlantic up to 400-500 miles from the northeastern United States, and sometimes, when the Santa Ana winds have been blowing, for several hundred miles westward toward Hawaii from the California coast.

FINE PARTICLES AND ESTHETICS

Such fine particles are particularly objectionable from the esthetic standpoint. The millions of Americans who travel to view such scenic wonders as the Grand Canyon, the Colorado Rockies and similar areas of scenic grandeur, will be greatly dismayed if they are unable to view these beautiful areas or can see them only in dim outline.

Present field and laboratory evidence also suggests that this is the size range of particles formed by gas to particle photochemical and dark reactions involving gases such as SO_2 NO_x, ozone, ammonia and hydrocarbons.

The reduced visibility as mentioned earlier is caused primarily by particles in the range of 0.1 to 1 micron in cross section. Such particles are the most effective in causing light scattering and thus reduced visibility, and have residence times in the atmosphere of many days.

With a better understanding of particle sources, the manner in which they move from where they are formed, an understanding of methods for identifying them and a better concept of the manner in which they are removed from the atmosphere, it will then be possible to evaluate the problem and to decide what measures must be taken to alter the present trend.

Without question, one of the most important problems in this context relates to visibility in the natural scenic areas of the southwest. If, for example, the ability of visitors to see features in the Grand Canyon, on Lake Powell, Monument valley or the Canyon lands area begins to deteriorate, it is of extreme importance to know what is causing such effects and whether the phenomenon is due to pollution plumes from Los Angeles or Las Vegas, from power plants like Mojave, Navajo, Kaiparowits or Four Corners, now operating or scheduled to be built, or from dust storms in Mexico or the Mojave Desert, or forest and brush fires in California, Nevada or Arizona.

THE NEED TO MEASURE FINE PARTICLES

I believe it is possible now to assemble information which will be needed in establishing the basic facts about the location of the sources of fine particles, the manner in which they are carried through the atmosphere and the sinks which finally cause them to disappear. There are a number of locations where fine particle measurements should be established without further delay. Such sites as mountain summits, isolated lakes, deserts and forests are ideal locations for monitoring the atmosphere.

There is a distinct paucity of data at the continental level concerning the spatial concentration of fine particles over the United States since the particulate data presently obtained by the National Air Quality Network of E.P.A. does not measure the small particles referred to in this paper. For more than fifteen years I have been measuring fine particles and during the past five years have been developing a major program on this subject at our University. We believe this to be the most important problem in air quality at the national and global level. During the past four years we have made ten flights across the United States to measure these parameters.[1]

MEASUREMENTS OF FINE PARTICLES ON THE GLOBAL SCALE

Based on these findings, we have come to realize the importance of measuring tropospheric concentrations of fine particles on the global scale. For several years we have been doing this[4] using merchant ships, and during the past spring spent more than a month in the Hawaiian Islands and on the German oceanographic vessel, "The Meteor," making such measurements. We have recently established a monitoring station of Pitcairn Island in the South Pacific and have just received a grant from N.S.F. to monitor small particulates in selected locations on the global scale. The objective of this latter study is to locate key stations for monitoring the clean air regions in the global troposphere so that a cooperative and meaningful effort to do this on a routine basis can be established within the next few years.

Our current activities at several locations in the United States permit us to utilize our knowledge of fine particles in these areas, taking advantage of the progress made during our global monitoring activities, evaluating and testing new techniques, equipment and procedures. We plan to supplement the measurement of fine particles with our new findings concerned with the turpentine effect[5] for evaluating the sources of small particles in such areas. This information should permit us then to prepare better guidelines for monitoring air quality throughout the country, and especially in areas polluted from anthropogenic sources.

My recent discovery of a new technique for monitoring ozone[6] is apparently sensitive to at least one part per billion so that this important substance can now be measured simply and easily on a second by second basis.

MEASUREMENT OF FINE PARTICLES OF LEAD

In addition to these ozone observations, our electron microscope studies of the size of lead particles from automobile exhaust [7] which are effective as nuclei for ice crystal formation in causing inadvertent cloud modification, also emphasizes the importance of fine particles. Lead compounds from auto exhaust, when exposed to iodine vapor, become lead iodide and are then highly effective nuclei for ice crystal formation. They have a submicroscopic cross section of 90-100 Å (0.009-0.01 microns). Our laboratory studies show that ice crystals readily form on such particles at -15°C and commonly have as their central nucleus small clusters of these primary particles in clumps or chains of 5 - 15 or more. These fine particles are far too small to serve as nuclei for water condensation. This fact is very important in relation to their effectiveness, since if liquid water condensed on them, it is quite possible that their ability to serve as a nucleus for ice crystal formation from the vapor phase would be destroyed since lead iodide, unlike silver iodide, is fairly soluble in water. [8]

There is some belief that the elimination of lead from automobile exhaust will remove the source of ice nuclei from polluted air. Our studies do not make us optimistic about this matter, at least for some time into the future.

A conservative estimate based on laboratory and field measurement indicates that the number of potential submicroscopic ice nuclei, presumably of a lead compound, emitted by an automobile using ordinary leaded gasoline and traveling fifty miles an hour is the order of 1×10^{12} fine particles of this type during an hour. In order to produce this number of ice nuclei, only ten parts per million of the lead compound in the gasoline needs to be utilized. This emphasizes that even the so-called non-leaded gasoline is likely to produce substantial numbers of potential ice nuclei unless it is highly refined and is not contaminated from bulk carriers that have not been thoroughly cleaned of leaded gas residues.

ACTIVATION OF FINE LEAD PARTICLES BY ATMOSPHERIC IODINE

In a recent paper, Moyers et al. [9] have shown that sufficient amounts of iodine are in the atmosphere to react with small lead residues. They point out that such reactions will likely take some time. This is in complete agreement with my field observations. I frequently observe that supercoooled convective clouds generally grow a thousand feet or so in thickness before they shift to ice crystals. This is most frequently seen at low level above and downwind of cities in air that is visibly polluted. Frequently stratiform clouds which are supercooled can be seen at higher altitudes in visibly cleaner air.

THE IMPORTANCE OF FINE PARTICLE MEASUREMENTS

The study, measurement and proper evaluation of the numbers and properties of fine particles in urban and country air comprises a whole new area of atmospheric research.

Many new problems confront us as we try to properly understand the complex interrelationships which exist. Both natural and anthropogenic sources must be considered in making these studies. New techniques involving surface chemistry, thin layer chromotography, aerobiology, gas to particle and synergistic reactions, gas absorption, electron probes and microscopy and similar techniques must be utilized if we are to make good progress in solving these interesting problems.

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